UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS LABORATORY

Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 575

Monitoring an Iron-Enhanced Sand Filter Trench for the Capture of Phosphate from Stormwater Runoff

Final Report for the Project:
Assessing Iron Enhanced Filtration Trenches

by

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and

Minnesota Pollution Control Agency

520 Lafayette Road North.

St. Paul, MN 55155

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Grant Project Summary

Project title: Assessing Iron Enhanced Filtration Trenches

Organization (Grantee): City of Prior Lake

Project start date: 1/1/2011 Project end date: 8/31/2015 Report submittal date: 10/05/2015

Grantee contact name: Pete Young Title: Water Resources Engineer

Address: 4646 Dakota Street SE

City: Prior Lake State: MN Zip: 55372

Phone number: 952-447-9831 Fax: ________ E-mail: pyoung@cityofpriorlake.com

Basin (Red, Minnesota, St. Croix, etc.) / Watershed & 8 digit HUC:: 70007200, 70005400 (DNR lake IDs) County: ________

Project type (check one):

- ☐ Clean Water Partnership
- ☐ Total Maximum Daily Load (TMDL)/Watershed Restoration or Protection Strategy (WRAPS) Development
- ☐ 319 Implementation
- ☒ 319 Demonstration, Education, Research
- ☐ TMDL/WRAPS Implementation

Grant Funding

Final grant amount: $239,999.99 Final total project costs: $496,570.99

Matching funds: Final cash: $0 Final in-kind: $256,571.00 Final Loan: $0

MPCA project manager: Gregory Johnson

For TMDL / WRAPS Development or TMDL / WRAPS Implementation Projects only

Impaired reach name(s): ________

AUID or DNR Lake ID(s): ________

Listed pollutant(s): ________

303(d) List scheduled start date: ________ Scheduled completion date: ________

AUID = Assessment Unit ID
DNR = Minnesota Department of Natural Resources

Executive Summary of Project

This monitoring project was performed on an iron enhanced sand filtration (IESF) trench in the City of Prior Lake. Water from the pond and IESF trench discharges into a wetland that ultimately drains into Upper Prior Lake. In 2002, Upper Prior Lake was listed on Minnesota's 303(d) List of Impaired Waters for nutrient/eutrophication biological indicators with aquatic recreation being impaired. Water quality has been reduced due to excessive phosphorus loading. According to the TMDL implementation plan developed for Spring Lake and Upper Prior Lake, the total phosphorus load must be reduced by 83% and 41%, respectively, to meet water quality goals.

Overall, for 28 monitored natural rainfall/runoff events from 2013-2015, the IESF trench removed 26% of the phosphate mass load it received, though after non-routine maintenance in August 2014 the performance improved to 45% phosphate mass load reduction. These results indicate the importance of maintenance. A newer installation was previously monitored, and found to retain 71% of the phosphate (Erickson and Gulliver 2010). Most of the overall phosphate load reduction was achieved during larger events that had comparatively high influent phosphate concentrations (32.3 – 125.2 μg/L) and mass loads. Many small events in this investigation with low influent phosphate concentrations (3.8 – 38.4 μg/L) or mass loads exhibited negative removal (i.e., effluent mass load > influent mass load). The high effluent phosphate concentrations are suspected to be caused by the degradation of floating plants (primarily duckweed) that were deposited on the surface of the filter trench. As mentioned above, non-routine maintenance to remove this material resulted in substantial performance improvement. After this maintenance, positive removal was observed for influent concentrations ranging from 6.3 – 44.1 μg/L. Detailed results, maintenance activities, design and operating & maintenance recommendations, and lessons learned are given within this report.

PROBLEM

This monitoring project was performed on an iron enhanced sand filtration (IESF) trench in the City of Prior Lake. Water from the pond and IESF trench discharges into a wetland that ultimately drains into Upper Prior Lake. In 2002, Upper Prior Lake was listed on Minnesota's 303(d) List of Impaired Waters for nutrient/eutrophication biological indicators with aquatic recreation being impaired. Water quality has been reduced due to excessive phosphorus loading. According to the TMDL implementation plan developed for Spring Lake and Upper Prior Lake, the total phosphorus load must be reduced by 83% and 41%, respectively, to meet water quality goals.

WATERBODY IMPROVED

In order to reduce phosphorus loading from stormwater runoff at pond 3B and other locations, the City of Prior Lake installed several iron-enhanced sand filter trenches. Iron enhanced sand technology has been shown to have the ability to retain phosphate (Erickson et al. 2007, 2012) and reduce phosphorus concentrations from stormwater. The main objectives of this project were to 1) monitor one such installation for its effectiveness with regards to phosphate removal over the course of several natural rainfall/runoff events and 2) develop design and maintenance recommendations for such installations. Although the quality of the effluent was improved, the impact this IESF trench had on the overall water quality of Upper Prior Lake was not evaluated.

PROJECT HIGHLIGHTS

This project, which was funded with US EPA 319 funds through the Minnesota Pollution Control Agency (MPCA), was a combined effort between St. Anthony Falls, University of Minnesota and the City of Prior Lake. Natural rainfall/runoff events were monitored during non-winter months from 2013 through 2015 to assess the performance of an iron enhanced filtration trench in the City of Prior Lake, MN. This stormwater treatment practice is designed to capture dissolved phosphorus (phosphate), reducing the phosphate load to Upper Prior Lake.

RESULTS

Overall, for 28 monitored natural rainfall/runoff events from 2013-2015, the IESF trench removed 26% of the phosphate mass load it received, though after non-routine maintenance in August 2014 the performance improved to 45% phosphate mass load reduction. These results indicate the importance of maintenance. A newer installation was previously monitored, and found to retain 71% of the phosphate (Erickson and Gulliver 2010). Most of the overall phosphate load reduction was achieved during larger events that had comparatively high influent phosphate concentrations (32.3 – 125.2 μg/L) and mass loads. Many small events in this investigation with low influent phosphate concentrations (3.8 – 38.4 μg/L) or mass loads exhibited negative removal (i.e., effluent mass load >

influent mass load). The high effluent phosphate concentrations are suspected to be caused by the degradation of floating plants (primarily duckweed) that were deposited on the surface of the filter trench. As mentioned above, non-routine maintenance to remove this material resulted in substantial performance improvement. After this maintenance, positive removal was observed for influent concentrations ranging from 6.3 – 44.1 µg/L. Detailed results, maintenance activities, design and operating & maintenance recommendations, and lessons learned are given within this report.

PARTNERSHIPS

This project was a close collaboration between the Minnesota Pollution Control Agency (grant funds sponsor), the City of Prior Lake (Grantee, In-Kind Match provider), the Prior Lake Spring Lake Watershed District (In-Kind Match Provider), The Scott County Watershed Management Organization (In-Kind Match provider), and the University of Minnesota (sub-grantee, In-Kind Match provider).

Acknowledgements

This project was a contract between the City of Prior Lake and the Minnesota Pollution Control Agency, who funded the project through the Federal Clean Water Act Section 319 grant program, project No. 38942, with Greg Johnson as Project Manager. Greg's assistance and support throughout this project is greatly appreciated. The City of Prior Lake subcontracted the monitoring effort to the University of Minnesota.

Support from the City of Prior Lake including Ross Bintner, Pete Young, Brian Welch, and City summer interns is greatly appreciated. In addition, the assistance and support from SAFL staff including Aaron Ketchmark, Poornima Natarajan, David Liddell, James Pham, Matt Simon, Maria Garcia-Serrana, Chunyue Jiang, and Tyler Olson is appreciated.

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Executive Summary

Problem

In 2002, Spring Lake and Upper Prior Lake were listed on Minnesota's 303(d) List of Impaired Waters for nutrient/eutrophication biological indicators with aquatic recreation being impaired (Wenck 2011, Kale et al. 2012). A single TMDL implementation plan, which was completed for both lakes, states that Spring Lake is eutrophic to hypereutrophic and does not meet state standards for phosphorus, chlorophyll-a, or Secchi disk depth (Wenck 2011, Kale et al. 2012). Upper Prior Lake is also eutrophic to hypereutrophic and does not meet state standards for phosphorus or chlorophyll-a. It barely meets the state standard for Secchi disk depth of 1.0 m.

Water quality has been reduced due to excessive phosphorus loading. According to the TMDL implementation plan developed for the lakes, in order to meet water quality goals Spring Lake and Upper Prior Lake require an 83% and 41% reduction in total phosphorus, respectively (Wenck 2011, Kale et al. 2012). Existing estimated phosphorus loads are as shown in Table 1. Target load reductions for MS4 permitted sources (City of Prior Lake, Spring Lake Township, Scott County, and MnDOT) are all 64% for Spring Lake and zero for Upper Prior Lake because Upper Prior Lake will meet standards if load reductions for Spring Lake are achieved.

Table 1. Existing estimated phosphorus loading and load allocation for A. Spring Lake and B. Upper Prior Lake (Wenck 2011, Kale et al. 2012).

A.

Phosphorus Source	Existing Load (lb/yr)	Allocation (lb/yr)
MnDOT	43.8	15.9
City of Prior Lake	1308.2	472.1
Scott County		
Construction stormwater		
Industrial stormwater		
Upstream lake	63	63
Watershed load	3595	636
Septic	263	0
Atmospheric	30	30
Internal	5161	607

B.

Phosphorus Source	Existing Load (lb/yr)	Allocation (lb/yr)
MnDOT	36.4	36.4
City of Prior Lake	382.6	382.6
Scott County		
Construction stormwater		
Industrial stormwater		
Upstream lake	2179	611
Septic	4	0
Atmospheric	16	16
Internal	2598	2027

Waterbody Improved

In order to reduce phosphorus loading from stormwater runoff at pond 3B and other locations, the City of Prior Lake installed several iron-enhanced sand filter trenches. Iron enhanced sand technology has been shown to have the ability to retain phosphate (Erickson et al. 2007, 2012) and reduce phosphorus concentrations from stormwater. The main objectives of this project were to 1) monitor one such installation for its effectiveness with regards to phosphate removal over the course of several natural rainfall/runoff events and 2) develop design and maintenance recommendations for such installations. Although the quality of the effluent was improved, the impact this IESF trench had on the overall water quality of Upper Prior Lake was not evaluated.

Project Highlights

This project, which was funded with US EPA 319 funds through the Minnesota Pollution Control Agency (MPCA), was a combined effort between St. Anthony Falls Laboratory, University of Minnesota and the City of Prior Lake. Natural rainfall/runoff events were monitored during non-winter months from 2013 through 2015.

Results

Overall, for 28 monitored natural rainfall/runoff events from 2013-2015, the IESF trench removed 26% of the phosphate mass load it received, though after non-routine maintenance in August 2014 the performance improved to 45% phosphate mass load reduction. These results indicate the importance of maintenance. A newer installation was previously monitored, and found to retain 71% of the phosphate (Erickson and Gulliver 2010). Most of the overall phosphate load reduction was achieved during larger events that had comparatively high influent phosphate concentrations (32.3 – 125.2 µg/L) and mass loads. Many small events in this investigation with low influent phosphate concentrations (3.8 – 38.4 µg/L) or mass loads exhibited negative removal (i.e., effluent mass load > influent mass load). The high effluent phosphate concentrations are suspected to be caused by the degradation of floating plants (primarily duckweed) that were deposited on the surface of the filter trench. Non-routine maintenance, which included removal of the surface layer (~1-2 inches), resulted in substantial performance improvement. After this maintenance, positive removal was observed for influent concentrations ranging from 6.3 – 44.1 µg/L. Detailed results, maintenance activities, design and operating & maintenance recommendations, and lessons learned are given within this report.

Work Plan Review

Approved changes: There were four change orders approved during the project, as follows: Change order No. 1 was to reduce budget cost to reflect a reduction in funding, and was undertaken before the project began. Change orders Nos. 2 and 3 were to reflect changes in staff that occurred during the project. Change order No. 4 was to allow for telecommunication expenses at the site. There were no amendments to the project.

Objective 1. Design and Construction

Task 1a. Design and construct iron enhanced filter trenches. Design and construct field installations of the iron-enhanced filtration trenches as part of the City of Prior Lake's 2011 Water Quality Retrofit Project. Design and construction of iron enhanced filtration trenches were completed as scheduled.

Objective 2. Conduct Field Monitoring

Task 2a. Install monitoring equipment. City of Prior Lake's pond 3B was selected for installation of field monitoring equipment. The equipment that was installed included a tipping bucket rain gauge, air temperature sensor, data logger, automatic water samplers, water pressure transducers, solar panels, and deep cycle marine batteries.

Task 2b. Field monitoring. The performance of the iron enhanced sand filter (IESF) trench was monitored during natural rainfall/runoff events for more than two rainy seasons. Monitoring began in late June 2013 and continued until the end of October of that year. Monitoring equipment was removed for the winter and reinstalled in April 2014 where it remained until early October 2014. In 2015 monitoring equipment was installed in mid-June and events were monitored through the end of July. In all, a total of 28 natural rainfall/runoff events were monitored.

Task 2c. Chemical analysis. Water samples were analyzed at St. Anthony Falls Laboratory (SAFL) for phosphate (i.e., soluble reactive phosphorus, SRP) with duplicate samples periodically delivered to Instrumental Research, Inc. in Fridley, MN, a Minnesota Department of Health certified laboratory, to verify the accuracy of results obtained at SAFL. Analysis of these duplicate samples showed that the root mean square difference was approximately 7 μg/L for the range of samples tested (1.5 – 197 μg/L).

Field monitoring was completed as scheduled.

Objective 3. Data Analysis

Task 3a. Field monitoring data analysis. Monitoring results were analyzed by concentration based, load based, and percent exceedance methods (Erickson, et al., 2013). Event, annual, and cumulative phosphate influent and effluent mass loads and event mean concentrations were determined along with the percent capture (or retention) of these loads by the IESF trench. Data Analysis was completed as scheduled.

Objective 4. Public Outreach and Education

Task 4a. Establish partnerships. Partnerships have been established with the Minimum Impact Design Standards (MIDS) team and others for the review and dissemination of knowledge gained. Two meetings (3/23/2011 & 4/6/2012) of a technical advisory committee were held to make sure that the project met the needs of the practicing community.

Task 4b. Dissemination. Results will be disseminated through UPDATES, an email stormwater newsletter distributed to more than 2400 subscribers. Presentations have included the conceptual design of IESF trenches as installed in Prior Lake and have communicated the ability of iron enhanced sand filtration to retain phosphate. It is estimated that these efforts have reached over 1000 participants. Task 4c. Incorporation into education program. Results were, and will continue to be incorporated into Stormwater 'U' courses and workshops. Results have also been included in senior and/or graduate urban hydrology classes at the University of Minnesota and Valparaiso University, Valparaiso, IN.

Objective 5. Publish Final Design Standards and Final Report

Task 5a. Progress reports. Progress reports have been submitted on time, as scheduled.

Task 5b. Prepare and submit design standards for publication. Design standards with expected performance criteria, recommendations for maintenance, and lessons learned are included in this final report.

Task 5c. Prepare and submit a draft final report. This task has been completed with the submittal of this draft final report for MPCA review.

Task 5d. Prepare and submit final report. Comments on the draft final report were addressed and/or incorporated into the final report.

Grant Results

Introduction

Water-borne phosphorus can be present either in particulate (> 0.45 μm) or dissolved (< 0.45 μm) forms. Dissolved phosphorus in stormwater runoff and surface water bodies is mostly in the form of phosphate (H_XPO_4) (Stumm and Morgan 1981), which can be absorbed by phytoplankton. In temperate fresh surface waters, phosphate is typically the limiting nutrient of plant growth (Aldridge and Ganf 2003, US EPA 1999, Schindler 1977) due to its higher bioavailability factor (Sharpley et al., 1992). Sources of phosphate in urban stormwater runoff include lawn fertilizers, leaf litter, grass clippings, unfertilized soils, detergents, and rainfall, among others (American Public Health Association, 1998; U.S. EPA, 1999).

Nuisance algae blooms create negative aesthetic and eutrophic conditions in water bodies and can be generated by phosphorus. Such phosphorus loading can be caused by stormwater runoff, which typically contains significant amounts of phosphate, as well as the combination of all forms of phosphorus (total phosphorus). Studies have shown that total phosphorus in stormwater runoff from nationwide highway and urban areas comprises 30 – 45% dissolved phosphorus (phosphate) on average (Kayhanian, et al. 2007; Pitt et al. 2005), but ranges from 3 – 100% (Erickson et al. 2007). Thus, stormwater runoff can significantly increase the phosphate loads received by surface water bodies and, as a result, can contribute to or cause algae blooms and lake eutrophication.

As of 2014 in Minnesota, 573 water bodies have been designated as impaired due to nutrient/eutrophication/biological indicators that exceed water quality standards (MPCA 2015). This is 14% of the total 4114 impaired water bodies in the state. One of these water bodies is Spring Lake, which flows into Upper Prior Lake, located in the cities of Prior Lake and Spring Lake Township, MN. Spring Lake is representative of many water bodies in that its watershed phosphate loads must be reduced in order to meet water quality standards. With many total phosphorus load reduction requirements in the range of 60 – 80% and a median phosphate fraction of 40% (often higher), phosphate removal must occur if watershed phosphorus load targets are to be achieved.

Particulate phosphorus removal can be achieved by common stormwater control measures (SCM) such as wet ponds, dry ponds, and filters through the mechanisms of sedimentation and/or filtration. Most SCMs, however, retain little or no phosphate. For example, wet detention basins can achieve approximately 80% total suspended solids removal and 50% total phosphorus removal.

To capture phosphate, a chemical adsorption or precipitation process can be incorporated into a SCM. Adding metals such as steel wool or elemental iron, for example, to sand filter media has been shown to have the ability to capture a significant amount of phosphate (Erickson et al., 2007, 2012). The elemental iron, when rusted, forms iron oxides, and as stormwater filtrates through the media, phosphate binds to the iron oxides via surface adsorption.

To reduce the phosphate load entering phosphorus-impaired water bodies such as Spring Lake and other water bodies, the City of Prior Lake, Minnesota installed several iron-enhanced sand filtration (IESF) trenches along the perimeter of existing wet detention basins in 2010 and 2011. The media of the IESF trenches consisted of construction sand (ASTM C33) and 5% or more (by weight) of iron shavings. In the IESF trench monitored for this project (Pond 3B), the amount of iron shavings was 5% by weight. In a preliminary test of two trenches, installed in a different pond (Erickson and Gulliver, 2010), with approximately 7.2% and 10.7% by weight iron filings, the phosphate retention varied from 28% for low inflow phosphate concentration to 86% at high inflow phosphate concentration, with an overall mean (using the pollutant load of 5 events) of 71% phosphate retention. These measurements were taken approximately six months after installation, so the filters were relatively new. The Minnesota Pollution Control Agency (MPCA) provided funding for the City of Prior Lake and the St. Anthony Falls Laboratory, University of Minnesota to monitor and assess one trench for its performance related to the capture of phosphate from stormwater runoff in years 3, 4 and 5 following construction. Thus, a main objective of this study was to determine phosphate retention of one trench and to investigate maintenance requirements. This was achieved by monitoring natural rainfall/runoff events over the course of three summer seasons.

Iron-Enhanced Sand Filtration Trench Design

The IESF trenches were designed with the filter surface at a new normal water level (NWL), below the water level control weir in the catch basin adjacent to the wet detention basin (Figure 1). When runoff flows into the wet detention basin, this design allows the water level in the pond to increase so that the surface of the sand filter becomes submerged and water filtrates vertically downward through the sand-iron media. After flowing through the media, the filtered runoff enters a gravel reservoir where it is collected by a 4-inch diameter perforated PVC pipe drain tile and conveyed to the outlet structure (i.e., catch basin) of the wet detention basin. For small rainfall events that do not increase the water level above the water level control weir crest, all water flows through the iron-sand filter until the water surface elevation returns to the NWL. In large runoff events, the filter treats the first portion of the increase in wet basin storage volume while excess volume flows over the water level control weir and bypasses the filter. Once the water level in the pond drops to below the control weir crest, the remaining excess water in the pond passes through the IESF trench. The trenches are lined with an impermeable liner such that only stormwater that has been filtered by the trench enters the drain tile and water only enters the IESF trench through the top surface. Once stormwater enters the filter, the only way for it to leave the system is through the drain tile.

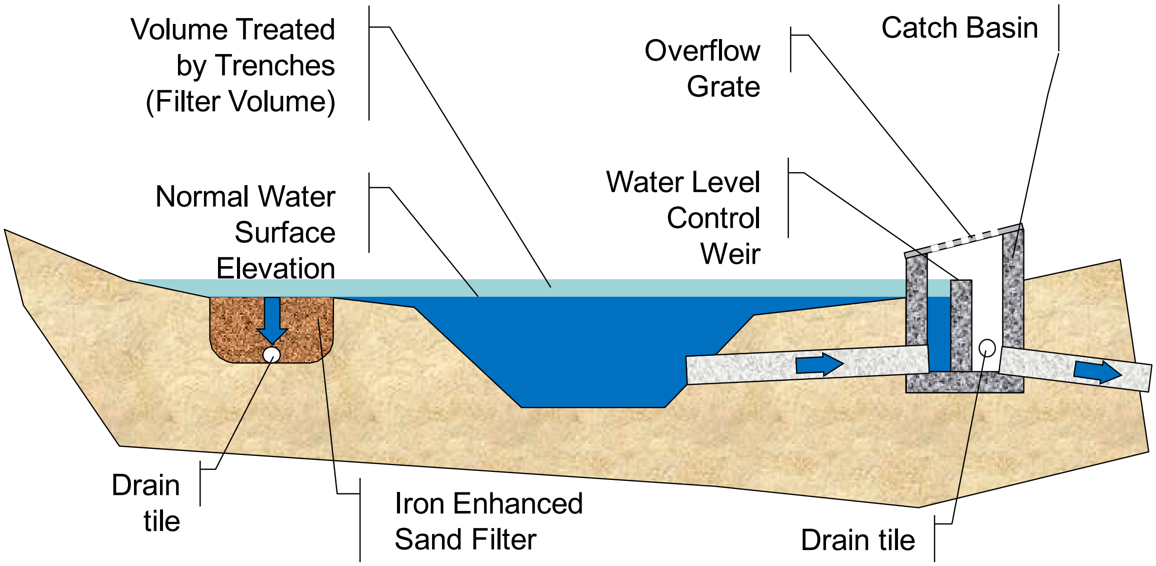


Figure 1. Iron-enhanced sand filtration trench schematic.

It should be noted that to remain functional and allow for continued rusting of the iron particles (and the creation of more sorption sites), the filter media must dry out between runoff events (Erickson et al. 2007, 2012). This is achieved by having the elevation of the drain tile outlet (i.e., discharge location) above the water level at the discharge location (i.e., within the catch basin in this case). This allows air to reach the media through the drain tile and, when the pond water level is lower than the filter, air can also reach the media through the IESF surface. The impermeable liner prevents adjacent groundwater from filling the media and air is in contact with the media at the surface and underneath via the drain tile, which promotes filter media drying between runoff events.

Site Selection

This monitoring project was performed in the City of Prior Lake at their Pond 3B (N 44.7108, W 93.4603), which is located just south of Knollridge Drive NW and just west of Northwood Road NW in Prior Lake, MN (Figure 4). Water draining from the pond discharges to a wetland that ultimately drains into Upper Prior Lake. Upper Prior Lake also receives water through a natural drainage channel from Spring Lake, which is located just to the south and west of Upper Prior Lake. Upper Prior Lake has a total watershed area of 16,116 acres, much of which is being or will be developed. The lakes and subwatersheds are shown in Figure 2 and Figure 3 (Wenck 2011, Kale et al. 2012).

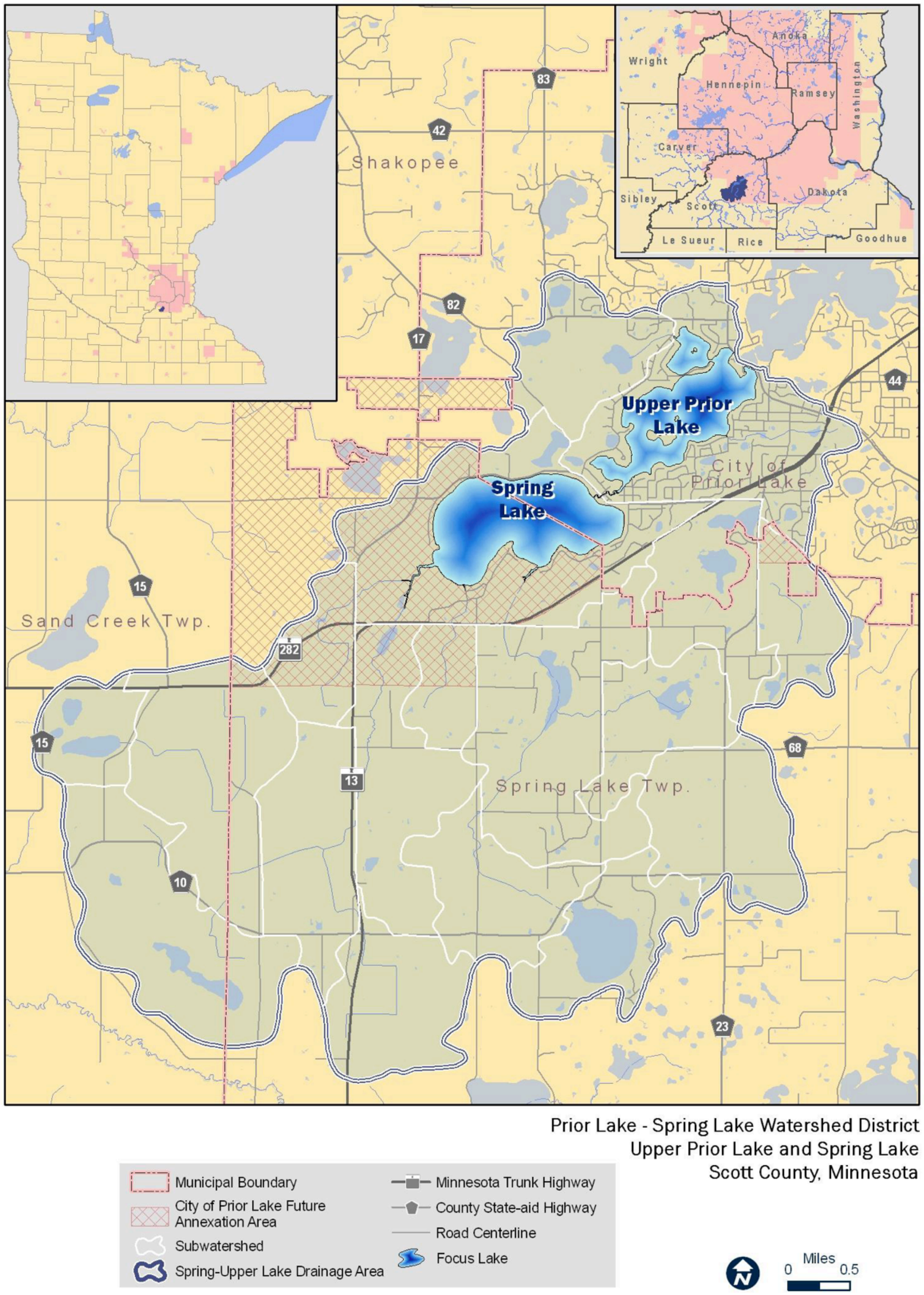


Figure 2. Location of Spring Lake and Upper Prior Lake (Wenck 2011, Kale et al. 2012).

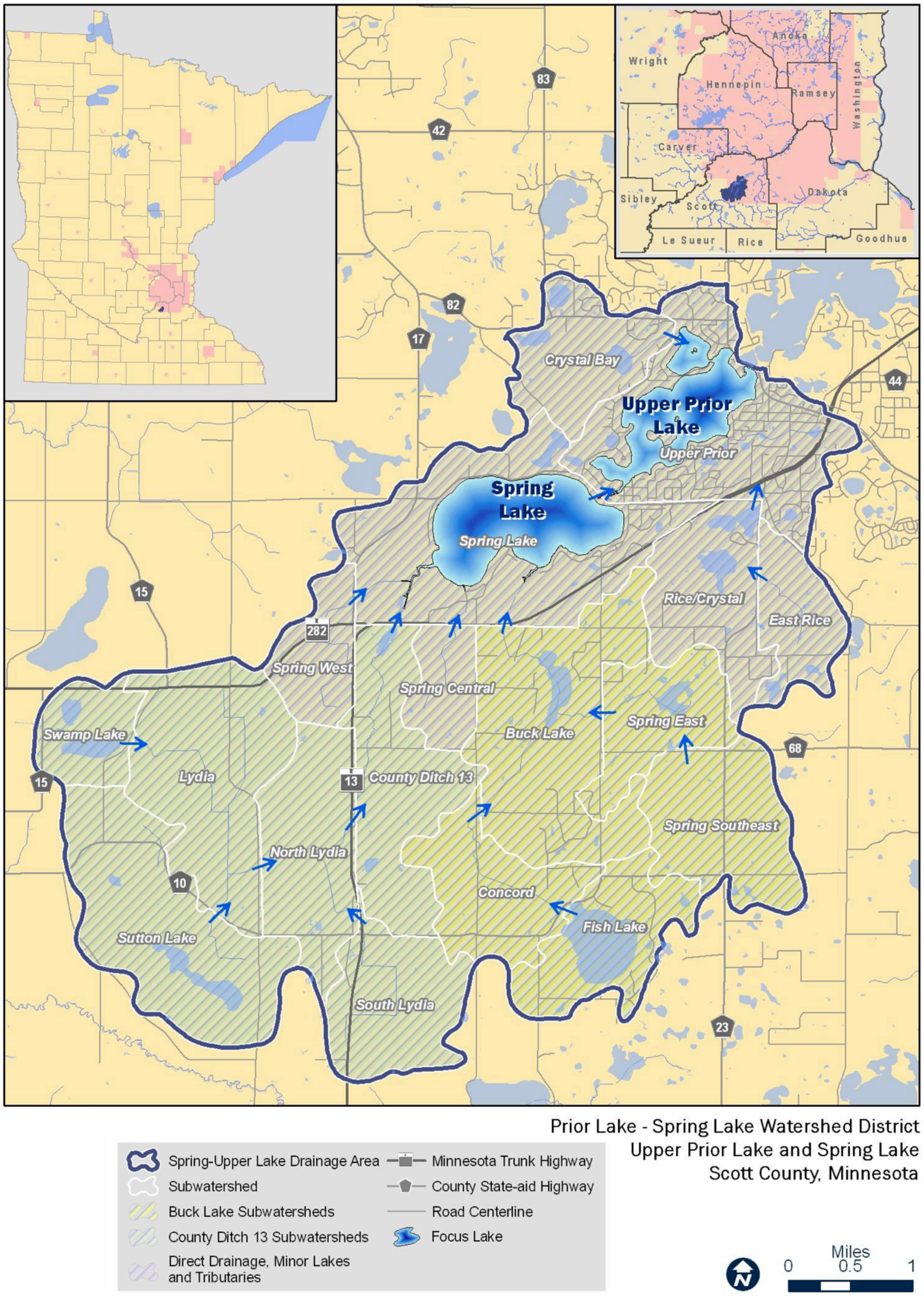


Figure 3. Spring Lake and Upper Prior Lake subwatersheds (Wenck 2011, Kale et al. 2012).

Figure 4. Monitoring site location (image courtesy of Google maps).

This site was chosen because the outlet of the drain tile had enough elevation change to the downstream receiving water body to allow for the flow measurement and sampling equipment to operate correctly. The flow measurement device (to be discussed in detail later) was a compound weir. In order for a compound weir to not interfere with the filter operation it must not back the water up into the sand filter, which could prevent it from drying between events. Also, weir operation is simplified when there is a free outflow. These scenarios require an elevation difference between the outlet drain tile and the receiving water body of approximately two feet, which was available at the chosen site.

Measurements

In order to determine the performance of the IESF trench with respect to phosphate removal, rainfall at the site and flow through the filter were measured and water samples were collected upstream of the filter and from the filter effluent (i.e., outflow from the drain tile). The phosphate concentrations of the influent and effluent water samples were determined, which enabled the percent phosphate retained (i.e., captured) in the filter to be calculated. All data was logged with a Campbell Scientific CR1000 data logger, and samples were collected by ISCO automatic samplers (described below). All equipment was powered by two, 12-volt deep cycle marine batteries located on site, except for the data logger, which had its own internal 12-volt battery.

Two Kyocera KC40T solar panels (43 W maximum power each) and a single Solarex SX10M solar panel (10 W maximum) sufficiently recharged the deep cycle marine batteries and the data logger internal battery, respectively, between runoff events.

Flow Rate Measurement

In order to measure expected flow rates, the 4-inch drain tile was extended by approximately 50 feet through the outlet pipe (3' diameter, reinforced concrete) of the catch basin to its discharge location near the receiving wetland. This extension was left installed through two winter seasons and became damaged, likely due to ice buildup in the 4-inch extension, the 3-foot concrete pipe, or both. This extension was replaced in June 2015. Future installations would benefit from rubber detachable couplings (e.g., Fernco) to allow for removal of this extension at the end of each rainy season.

At the outlet of the drain tile extension, the pipe was expanded to a 6-inch diameter PVC pipe through an eccentric expansion fitting shown in Figure 5. The 6-inch diameter pipe was then extended approximately 33 inches and a thin metal compound weir plate was attached to the end of the PVC pipe. A schematic of the compound weir cross-section is shown in Figure 6.

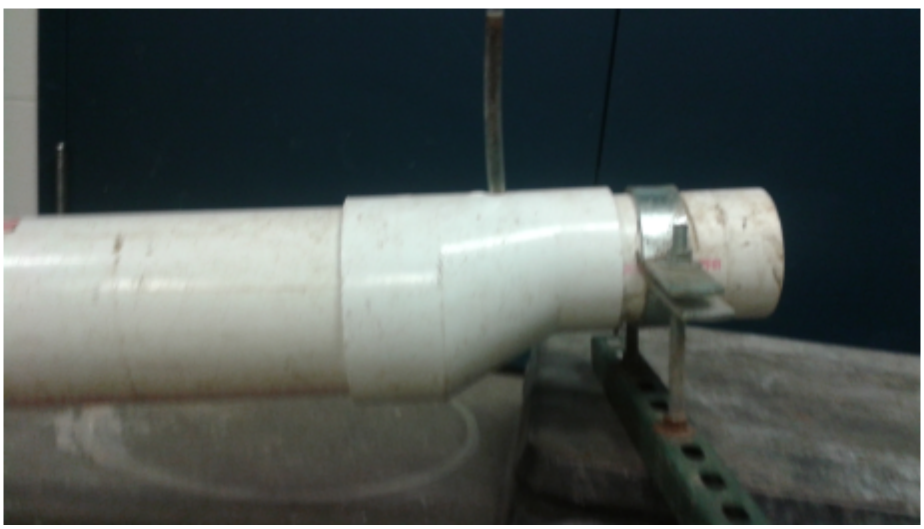


Figure 5. Expansion from 4 to 6-inch diameter pipe.

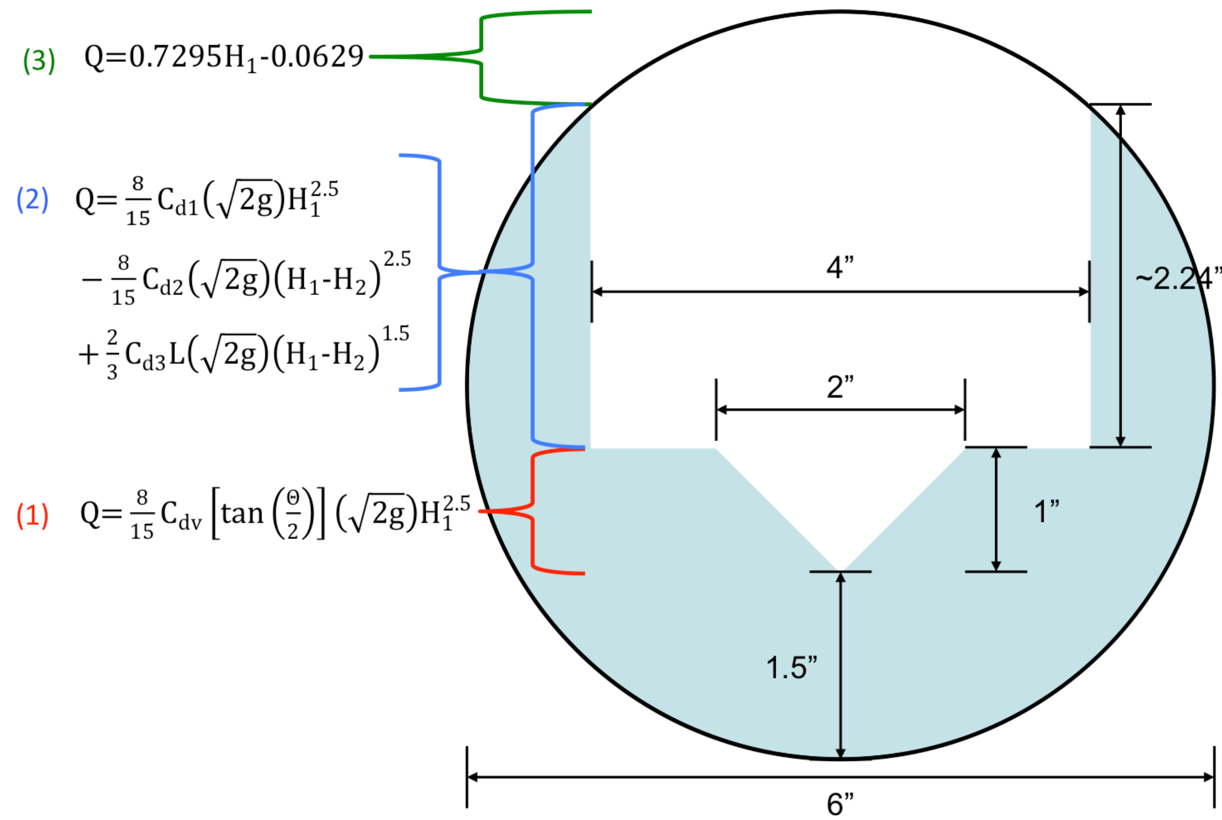


Figure 6. Schematic of compound weir cross-section with associated weir equations.

The head on the weir was measured using a Campbell Scientific CS-450 pressure transducer located in an adjacent vertical, ~2-inch diameter cylinder that was connected to the bottom of the 6-inch PVC pipe by means of one-quarter inch diameter flexible tubing (Figure 7). This arrangement allowed the water elevation in the vertical cylinder to match the water elevation in the 6-inch diameter discharge pipe, with the dampening of rapid fluctuations due to surface waves and turbulence, and a minimum of 3 inches of water above the transducer's sensor (necessary for improved accuracy).

Figure 7. Discharge end of 6-inch diameter pipe showing compound weir and vertical cylinder to contain a pressure transducer.

The head on the weir was used to calculate the flow over the weir (i.e., the flow through the sand filter), as shown in Figure 6. When flow was only through the V-notch section, the magnitude of the flow rate was determined by Equation 1.

$$Q = \frac{8}{15} C_{dv} \left[\tan\left(\frac{\Theta}{2}\right)\right] \left(\sqrt{2g}\right) H_1^{2.5} \tag{1}$$

where Q = discharge (cfs), C_{dv} = weir discharge coefficient (C_{dv} = 0.5916), Θ = angle of V-notch (90^o), and g = acceleration of gravity (32.2 ft/s^2), and H_1 = total head above the vertex of the V-notch (feet) (Franzini and Finnemore 1997).

When the flow level was above the top of the V-notch section (H = 1 inch = 0.0833 ft) and below the top of the vertical walls of the weir plate (H = 3.875 inch = 0.3229 ft), Equation 2 was used to calculate the flow rate.

$$Q=\frac{8}{15}C_{d1}\left(\sqrt{2g}\right)H_1^{2.5}-\frac{8}{15}C_{d2}\left(\sqrt{2g}\right)\left(H_1\text{-}H_2\right)^{2.5}+\frac{2}{3}C_{d3}L\left(\sqrt{2g}\right)\left(H_1\text{-}H_2\right)^{1.5} \quad (2)$$

where C_{d1}, C_{d2}, C_{d3} = weir coefficients (C_{d1} = 0.6799, C_{d2} = 0.5104, C_{d3} =0.5434) determined via calibration, H_2 = total depth of only the V-notch portion (1/12 foot), and L = combined length of the horizontal sections (1/6 foot) (Erickson et al. 2013).

When head, as measured by the pressure transducer, exceeded the top of the vertical walls of the weir plate, Equation 2 was no longer valid because Equation 2 assumes the vertical walls of the compound weir extend vertically upwards indefinitely. Thus, in this region, an empirical equation (3) was used to determine the flow rate.

$$Q=0.7295H_1\text{-}0.0629 \quad (3)$$

The transition between the compound weir (equation 2) and the empirical relationship above the compound weir (equation 3) occurs at H = 0.3229 ft. It was discovered, however, that a typo in the data logger program allowed the transition to occur at H = 0.229 ft, resulting in the abrupt change in flow rate shown in Figure 8. Analysis of the individual storm event data found that the error in volume associated with this typo was less than 2%. Flow rate predictions and calibration data for Equations 1, 2, and 3 for all three regions (i.e., V-notch flow, compound weir flow, and flow above the vertical walls of weir plate) are shown in Figure 8.

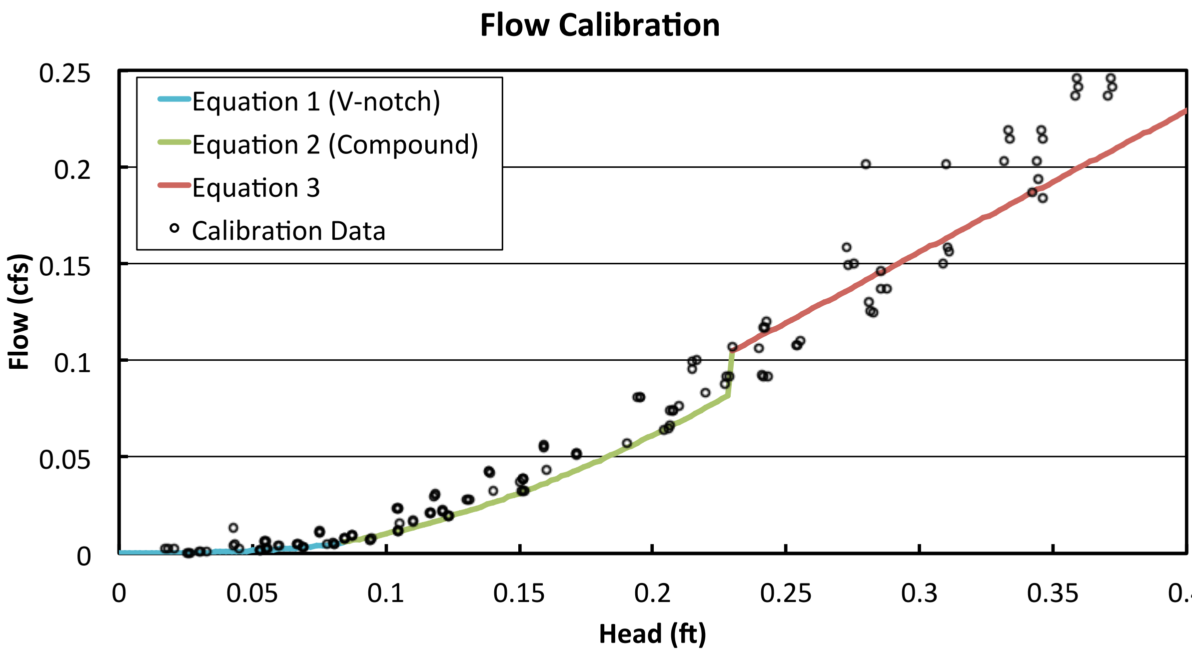


Figure 8. Weir equations for the three regions of the compound weir.

Because the IESF trench was lined with an impermeable barrier, it was assumed that the influent flow rate was equal to the effluent flow rate when at steady state. Therefore, flow was only measured at the discharge location and influent flow rates were not measured.

Rainfall Measurement and Ambient Conditions

Rainfall was measured by a Texas Electronics model TR-525I-R2 tipping bucket rain gauge located at the site. An Instrumentation Northwest PS9805 pressure transducer with an internal temperature sensor was located in the catch basin and was used to measure the water level elevation in the wet pond and the corresponding water temperature.

Water Sample Collection and Storage

An ISCO 6700 automatic water sampler was used to collect up to 24 discrete, time-based, influent samples (1000 mL bottles) per collection event. The sampling time increment was adjusted prior to each rainfall event based on the predicted rainfall depth and the availability of SAFL personnel to retrieve samples. Influent samples were collected from the wet pond adjacent to the IESF trench. The end of the influent sampling tube was installed within the wet basin, approximately one foot away from the edge of the IESF trench and weighted to ensure it was always fully submerged approximately 4 – 6 inches below the water level and at least 2 inches above the wet pond bottom.

For effluent samples, an ISCO 3700 automatic water sampler with 24 discrete bottles (1000 mL) was used. Different sampler models (6700 & 3700) were used due only to availability and had no impact on the monitoring process because the data logger program sent sample collection triggers to the samplers. The data logger was programmed to send a signal to the effluent sampler to collect 4 flow-weighted sub-samples (200 mL each) into each discrete bottle so that up to 96 effluent samples could be collected for each sampling event. Effluent samples were collected from within the 6-inch diameter PVC pipe, just upstream of the compound weir.

In some cases, effluent and/or influent grab samples were collected at the end of a sampling event when personnel were on site to retrieve samples. For the last event of 2015, influent and effluent sampling procedures were revised so that flow-weighted composite samples of influent and effluent water were collected simultaneously.

Sampling was initiated when thresholds on recorded rainfall depth and/or the measured head on the weir were surpassed. Thresholds were revised/updated periodically as experience was gained with the site and equipment. Typically thresholds were a head on the weir of 0.01 feet to 0.04 feet and/or a two-hour rainfall depth of 0.01 inches. When sampling commenced, an effluent sample was immediately collected. Subsequent effluent samples were collected on a flow-weighted basis with flow volume increments of 100 cubic feet or more, depending on the expected total depth of the rainfall event. For all but the last event of 2015, the first influent sample was collected at the next hour or half hour real time value after sampling was initiated. For example, if sampling began at 10:41 a.m., the first influent sample was collected at 11:00 a.m. or if sampling began at 11:03 a.m. the first influent sample was collected at 11:30 a.m. Influent sampling was time-based with each sampling event having two time-based increments. Initial samples were collected at one time increment up to a pre-programmed number of samples and all subsequent samples were collected at a different time increment. For example, the first 12 influent samples could be collected every 30 minutes and the last 12 samples could be collected every 3 hours.

In most cases water samples were retrieved from the site within 24 hours of the end of the sampling event and returned to SAFL where a portion of each sample (typically three separate ~15 mL sub-samples) was filtered through a 0.45-micron filter in preparation for analysis of soluble reactive phosphorus (phosphate). In rare instances, if sampling ended on a Friday evening or Saturday morning, samples may not have been collected until Monday morning. In 2013 each sub-sample was acidified with 1-2 drops of concentrated sulfuric acid and refrigerated. In 2014 and 2015 and filtered sub-samples were immediately frozen if they could not be analyzed immediately.

Water Sample Analysis

Phosphate concentrations of water samples were measured according to standard methods section 4500-P E - Ascorbic Acid (American Public Health Association, 1998) and Lachat Instruments (a Hach Company brand) Quick-Chem Method (R) 10-115-01-1-M. The latter method has a measurement range of 1 to 100 μg/L and a minimum detection limit of 0.1 μg P/L.

Samples were analyzed using a Lachat QuikChem 8000 series auto analyzer at SAFL. Duplicate samples were periodically delivered to Instrumental Research, Inc. in Fridley, MN to verify the accuracy of results obtained at SAFL. Analysis of these duplicate samples showed that the root mean square error was approximately 7 μg/L for the range of samples tested (1.5 – 197 μg/L).

This approach measured the soluble reactive phosphorus (SRP) of water samples collected in 2014-2015. Due to acid being added to the samples prior to storage in 2013, these samples may have been partially digested by the acid (converting particulate phosphorus to phosphate), which may have resulted in values higher than the actual SRP values that would have been obtained without acid addition. These samples were filter prior to acidification, which removed nearly all particulate phosphorus and there was no indication that partial digestion occurred.

Results and Discussion

The performance of the IESF trench was assessed by monitoring natural rainfall/runoff events for parts of each year from 2013 through 2015. Monitoring began in late June 2013 and continued until the end of October 2013. Monitoring equipment was removed for the winter and reinstalled in April 2014 where it remained until early October 2014. In 2015, monitoring equipment was installed in mid-June and events were monitored through the end of July.

Data was compiled and separated (or grouped) into "events." The end of an event was indicated by the flow through the filter declining to zero or near zero. Thus, an event was not necessarily a single rainstorm but rather a complete filtering event. For example, in some cases a rainstorm occurred and the filter was still filtering runoff when additional rain generated more runoff. When this occurred, all samples and corresponding data were grouped into a single event.

Additionally, in 2014 it was observed that a small trickle of flow (~ < 0.02 cfs) continued to pass through the filter long after the most recent rainstorm. This was attributed to a small, low area in the filter where the impermeable barrier encasing the filter media was also lower. The low area allowed a small portion of the sand media to accept and infiltrate water from the wet pond. While this did not allow a small portion of the filter to dry between rainfall events, it was assumed that this flow occurred in only a small fraction of the filter and that the majority of the filter did dry out. Thus, if the flow declined to a trickle and remained essentially constant, it was determined that the end of an event had been reached and the data was grouped accordingly.

Finally, June 2014 was one of the wettest months on record and included frequent smaller storms. A large storm (approximately 6.4 inch depth) occurred on June 14, 2014. Frequent events could have prevented the filter from drying out for many days or weeks, and the large event could have led to atypical runoff characteristics. Beginning in July 2014 the filter began to infiltrate water at a much slower rate, presumably due to surface clogging. In some cases the filter would remain submerged for days (Figure 9) with flow through the filter remaining essentially constant (~ 0.1 - 0.2 cfs). In this case, if a day or more without rain occurred between rainfall events and the two rainfall events were clearly part of separate weather systems, the two storms (and all corresponding data) were considered separate events. It should be noted that, in August 2014, non-routine maintenance was performed on the sand filter. As will be discussed later, this maintenance improved flow through the filter for the remainder of 2014 and through the end of the monitoring period in 2015. At the time monitoring ended in late July 2015, flow through the filter still occurred at satisfactory rates.

With this grouping of events, the performance of the IESF trench was assessed for a total of 28 events (8 in 2013, 15 in 2014, and 5 in 2015). Based on the results, a series of recommendations for design, operation, and maintenance are included in Appendix A.

Figure 9. Submerged IESF trench in early August 2014.

Events and Performance

Information regarding each of the events that were monitored is shown in Table 2, and total annual values are shown in Figure 10. For events 3 through 6, valid rainfall data was not obtained due to rain gage errors. If possible, nearby rainfall daily amounts were obtained from Weather Underground (http://www.wunderground.com/). For event 4, no rainfall was recorded at any nearby rain gauge. Thus, the rainfall depth for that event is listed as "unknown."

Also, for event 25, due to the ground wire of the influent sampler being disconnected from the data logger, more influent samples were collected by the sampler (24) than were recorded by the data logger (16). Due to the fact that there was no method to determine what samples were the extra samples, the average phosphate concentration of all 24 bottles was used as the concentration of each of the 16 bottles recorded by the data logger and used in analysis. With an average influent concentration of the 24 bottles of 3.7 μg/L (range 2.0 to 6.2 μg/L) and a standard deviation of 0.7 μg/L, any error associated with this method was deemed acceptable.

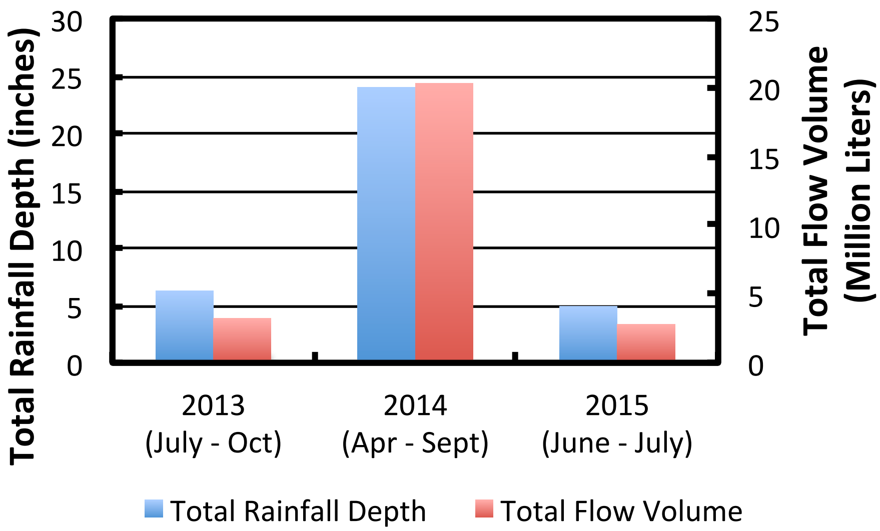


Figure 10. Annual Rainfall and Total Flow Volume. Note that flow volume denotes water that passed through the IESF trench.

Rainfall-runoff relationships and "pollutographs" (concentration versus time) for Event 1 are shown in Figure 11 and Figure 12, respectively, and provided in Appendix B for each event listed in Table 2. In cases where rainfall estimates were obtained from the Weather Underground, rainfall as a function of time was not available. Thus, the daily rainfall total precipitation was plotted as one instantaneous rainfall on the graph beginning at the time of the first recorded rainfall.

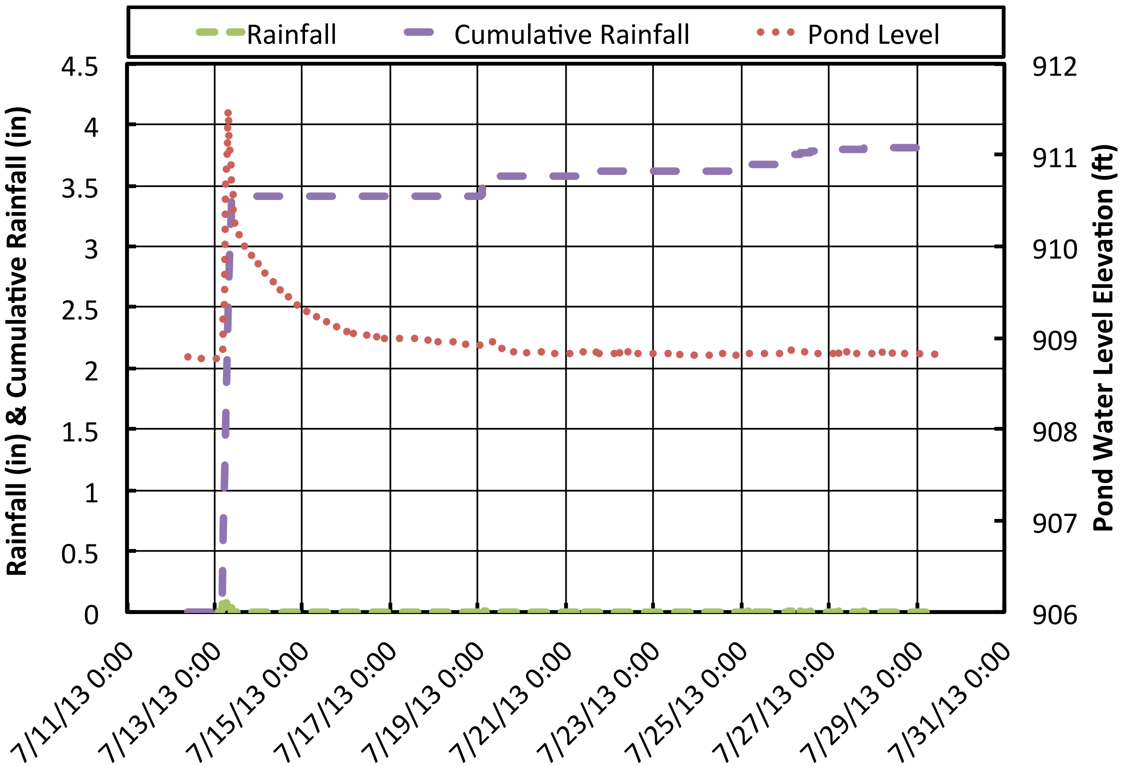


Figure 11. Rain and pond level for event 1.

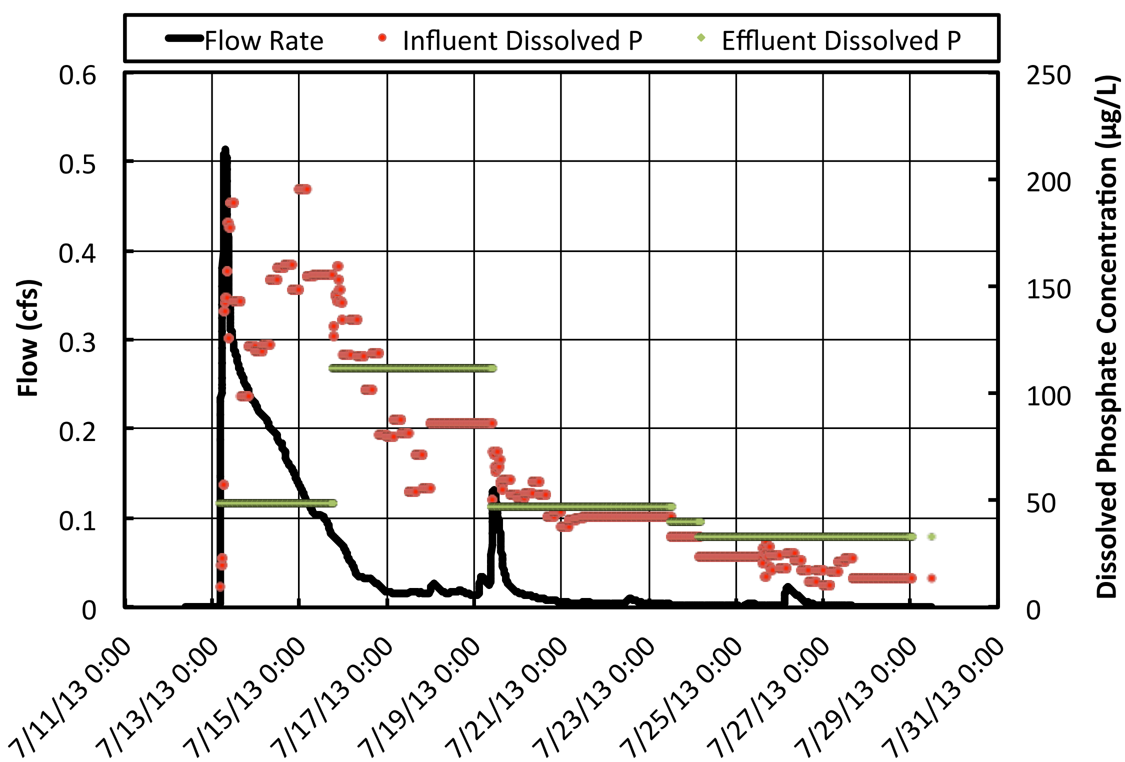


Figure 12. Flow and Pollutograph for event 1.

For some events, effluent samples were combined before analysis so that only the effluent event mean concentration (EMC) was determined. In these cases, the effluent phosphate EMC appears as a horizontal line on the pollutograph, as shown in Figure 12. Influent samples were time-based, and thus cannot be combined into a composite sample (Erickson et al. 2013). Therefore, influent samples appear as individual sample concentrations (i.e., dots). Note that some influent samples appear as horizontal lines (see Figure 12, from 7/18/13 through 7/19/13) because long duration events filled all sample bottles. Horizontal lines were used to indicate that the no new samples were collected during this period. Sampling resumed when samples were retrieved and samplers were reset, as indicated by influent samples appearing as individual concentrations.

Table 3 lists the total mass load of phosphate in the influent and effluent for each event, for each year, and for the entire monitoring period along with the corresponding influent and effluent EMCs and percentage of phosphate retained. Due to the assumption that the influent flow rate was equal to the effluent flow rate (i.e., there was no infiltration), the percent phosphate retained as computed by EMC values and mass loads are identical (Erickson et al. 2013).

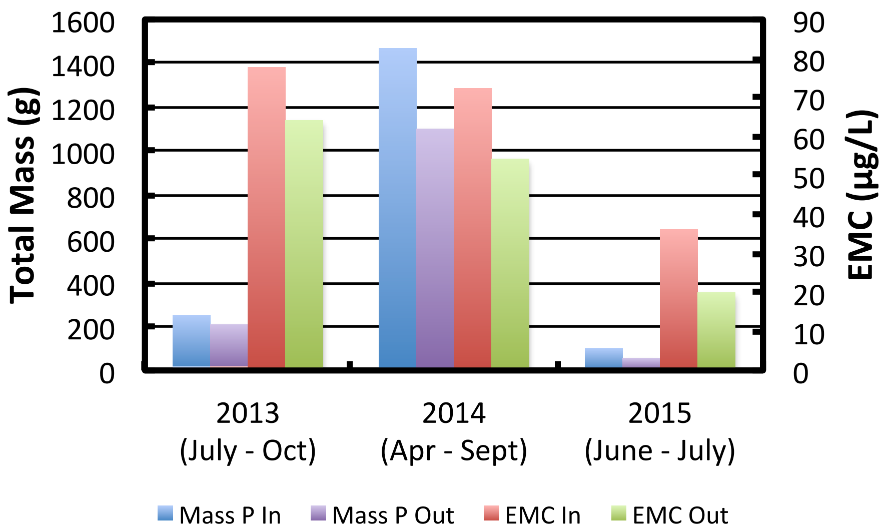


Figure 13. Annual mass load and event mean concentration (EMC).

As listed in Table 3 and shown in Figure 13, the percent phosphate retained in 2013, 2014, and 2015 was 18%, 25%, and 45%, respectively. Overall retention for all events was 26%. Half of the events (14 out of 28) were found to have negative removal (i.e., effluent mass loads > influent mass loads). These events tended to be smaller events with very low influent phosphate concentrations (3.7 – 39.4 µg/L). This appears to be at least partially due to the accumulation of organic phosphorus in or on the filter media such that the degradation of this organic material (conversion of particulate phosphorus to soluble phosphate) caused an increase in the effluent phosphate concentration. Routine maintenance periodically removed this material (as documented in Table 3), which likely had a positive impact on filter performance, but was not measured by this project. Non-routine maintenance in August 2014 involved the removal of the top layer of sand (~1-2 inches) and associated organics and grey muck, and had a significant impact on performance. As will be discussed later, non-routine maintenance actions that included removing accumulated solids from the surface of the filter improved the performance of the IESF for events that had a low influent phosphate concentration. Another possibility is that equilibrium driving forces (i.e., concentration differences) caused phosphate to be released from the media at low concentrations and retained at high concentrations, but this effect has not been documented in any other IESF installation and is thus unlikely to cause a significant impact on filter performance.

Maintenance was performed on the IESF trench since installation, and maintenance performed during this project is listed in Table 3. Routine maintenance occurs on a regular, relatively frequent schedule (Erickson et al. 2013) and for this project included inspection, weeding, raking, and breaking up iron clumps. Non-routine maintenance occurs only as required by a change in performance, and thus occurs on an irregular, often infrequent schedule (Erickson et al. 2013). Non-routine maintenance was only performed once on this IESF trench between January 2011 (installation) and September 2015, and occurred in August 2014. This non-routine maintenance occurred after event 19 and involved scraping the media surface, removing accumulated solids (including grey muck) at or near the filter media surface, and breaking up clumps of iron particles that had formed. After this non-routine maintenance was performed, four events were monitored in 2014 and five events in 2015. Other routine maintenance actions (weeding and raking) were performed over the monitoring period but the August 2014 non-routine maintenance was the most intensive. All maintenance actions are presented in detail in the following section.

Table 2. Events monitored. Note that flow volume denotes water that passed through the IESF trench.

Year	Event	Date of First Rainfall	Total Rainfall Depth (inches)	Total Flow Volume (L)
2013	1	07/13/13	3.81	1,724,260
	2	08/05/13	0.03	281,869
	3	08/06/13	0.28	155,012
	4	unknown	unknown	203,274
	5	09/19/13	0.24	143,623
	6	10/02/13	0.66	161,741
	7	10/14/13	1.02	546,348
	8	10/17/13	0.24	35,849
2013 Totals			**6.28**	**3,251,975**
2014	9	04/19/14	0.33	79,498
	10	04/23/14	4.50	4,241,457
	11	05/10/14	1.18	1,462,550
	12	05/19/14	0.76	635,323
	13	05/27/14	0.11	75,198
	14	05/31/14	3.56	2,380,296
	15	06/07/14	0.73	542,913
	16	06/14/14	6.38	6,803,571
	17	06/28/14	1.47	856,248
	18	07/11/14	1.94	1,119,003
	19	07/25/14	0.68	719,763
	20	08/17/14	1.39	835,301
	21	08/19/14	0.39	357,164
	22	09/10/14	0.10	40,490
	23	10/01/14	0.50	157,097
2014 Totals			**24.02**	**20,305,874**
2015	24	06/17/15	0.06	5,461
	25	06/27/15	0.77	239,274
	26	06/29/15	0.17	27,397
	27	07/06/15	2.28	1,332,210
	28	07/12/15	1.65	1,195,410
2015 Totals			**4.93**	**2,799,752**
Grand Totals			**30.30**	**26,357,601**

Table 3. Phosphate (P) loads, concentrations, and retention.

Year	Event	Mass P In (g)	Mass P Out (g)	EMC In µg/L	EMC Out µg/L	Percent P Retained %
2013	1	215.9	98.6	125.2	57.2	54%
	Routine Maintenance: weeded & raked					
	2	3.3	41.6	11.7	147.5	-1163%
	3	2.1	5.5	13.2	35.7	-170%
	4	2.3	22.0	11.5	108.3	-843%
	5	11.9	7.3	82.6	50.6	39%
	6	1.9	4.0	11.5	24.7	-115%
	7	14.2	28.4	26.0	52.0	-100%
	8	1.2	0.9	32.3	26.4	18%
2013 Totals		253	208	77.7	64.1	18%
2014	9	0.6	3.7	8.1	46.2	-470%
	10	438.8	320.6	103.5	75.6	27%
	11	85.6	56.8	58.5	38.8	34%
	12	23.2	34.9	36.5	54.9	-50%
	Routine Maintenance: weeded and raked					
	13	0.3	3.1	3.8	41.3	-981%
	14	263.4	150.4	110.7	63.2	43%
	15	21.4	39.1	39.4	71.9	-83%
	16	539.1	367.4	79.2	54.0	32%
	17	46.7	46.3	54.5	54.1	1%
	18	17.7	32.1	15.8	28.7	-82%
	Routine Maintenance: raked algae					
	19	7.2	21.0	10.0	29.2	-192%
	Non-Routine Maintenenance: raked, removed surface solids, broke up iron clumps					
	20	11.5	16.0	13.7	19.1	-39%
	21	5.9	4.7	16.4	13.1	20%
	22	0.7	0.5	17.0	13.4	22%
	23	6.7	4.7	42.8	29.7	31%
2014 Totals		1469	1101	72.3	54.2	25%
2015	Routine Maintenance: weeded, broke up iron clumps					
	24	0.034	0.031	6.3	5.7	10%
	25	0.9	4.8	3.7	20.0	-436%
	26	0.2	0.6	6.6	22.6	-243%
	27	47.4	29.3	35.6	22.0	38%
	28	52.7	21.1	44.1	17.6	60%
2015 Totals		101	56	36.2	19.9	45%
Grand Totals		1823	1351	69.1	51.2	26%

Prior to the non-routine maintenance in August 2014, positive removal was observed for eight events with influent phosphate concentrations of 32.3 – 125.2 μg/L, while negative removal was observed for eight events with influent concentrations of 3.8 – 39.4 μg/L (see Table 3 and Figure 14). This illustrates that in general, positive removal occurred during events with higher influent phosphate concentration and negative removal occurred during events with lower influent phosphate concentration. After non-routine maintenance, positive removal was observed for six events with influent phosphate concentrations of 6.3 – 44.1 μg/L, while negative removal was observed for three events with influent concentrations of 3.7 – 13.7 μg/L. After non-routine maintenance, positive removal occurred during events with influent phosphate concentration similar in range to the events with negative removal before non-routine maintenance (negative removal for 3.8 – 39.4 μg/L before non-routine maintenance vs. positive removal for 6.3 – 44.1 μg/L after non-routine). In addition, the range of influent phosphate concentration for which positive removal occurred was considerably lower (32.3 – 125.2 μg/L before vs. 6.3 – 44.1 μg/L after). Finally, the range in influent concentration for events with negative removal was smaller after non-routine maintenance compared to before non-routine maintenance (3.8 – 39.4 μg/L before vs. 3.7 – 13.7 μg/L after). This suggests that the non-routine maintenance performed in August 2014 substantially improved performance of the IESF, particularly when influent phosphate concentrations were low.

The first event after non-routine maintenance (event 20) had less negative removal (-39%) than the previous two events (-82% and -139%) with approximately the same influent EMC (~10-16 μg/L). The next two events (21 and 22) had approximately the same influent EMC (~16-17 μg/L) but achieved 20% and 22% phosphate retention (positive removal). The final event of 2014 had an influent EMC of over 40 μg/L and 31% retention was achieved. The non-routine maintenance actions were effective in improving the phosphate retention of the filter and that the negative retention observed in the first event after the non-routine maintenance is believed to be due to the IESF media being washed of loosened and excess phosphate-bearing material. Thereafter, the positive effect of non-routine maintenance is supported by the increase in observed phosphate retention rates at similar EMCs.

In 2015 the performance of the IESF trench continued to exhibit improved effectiveness. The first event of 2015 had an influent concentration of 6.3 μg/L and still exhibited a slight positive retention (i.e., 10%). The next two events, however, also had low influent concentrations (< 7 μg/L) but had effluent concentrations of about 20 μg/L. The final two events of 2015 had influent concentrations of approximately 36 and 44 μg/L and with effluent concentrations again of approximately 20 μg/L, and phosphate retention was 38 and 60%, respectively. The phosphate removal at low influent concentrations early in 2015 and the increase in overall removal compared to the previous two years (45% compared to 25% and 18%), demonstrate the impact and importance of routine and non-routine maintenance.

In 2013 the effluent EMCs ranged from about 25 to 52 µg/L (except for events 2 and 4, which appear to be anomalies). Events in 2014 prior to non-routine maintenance (August 2014) had effluent EMCs ranging from 29 to 72 µg/L. After non-routine maintenance, the effluent EMCs of storm events in 2014 and 2015 ranged from 5.7 to 22.6 µg/L. This illustrates that the effluent EMC for storm events in 2013 and 2014 before non-routine maintenance were larger than effluent EMCs after non-routine maintenance was performed, even for events with similar influent EMCs (see above).

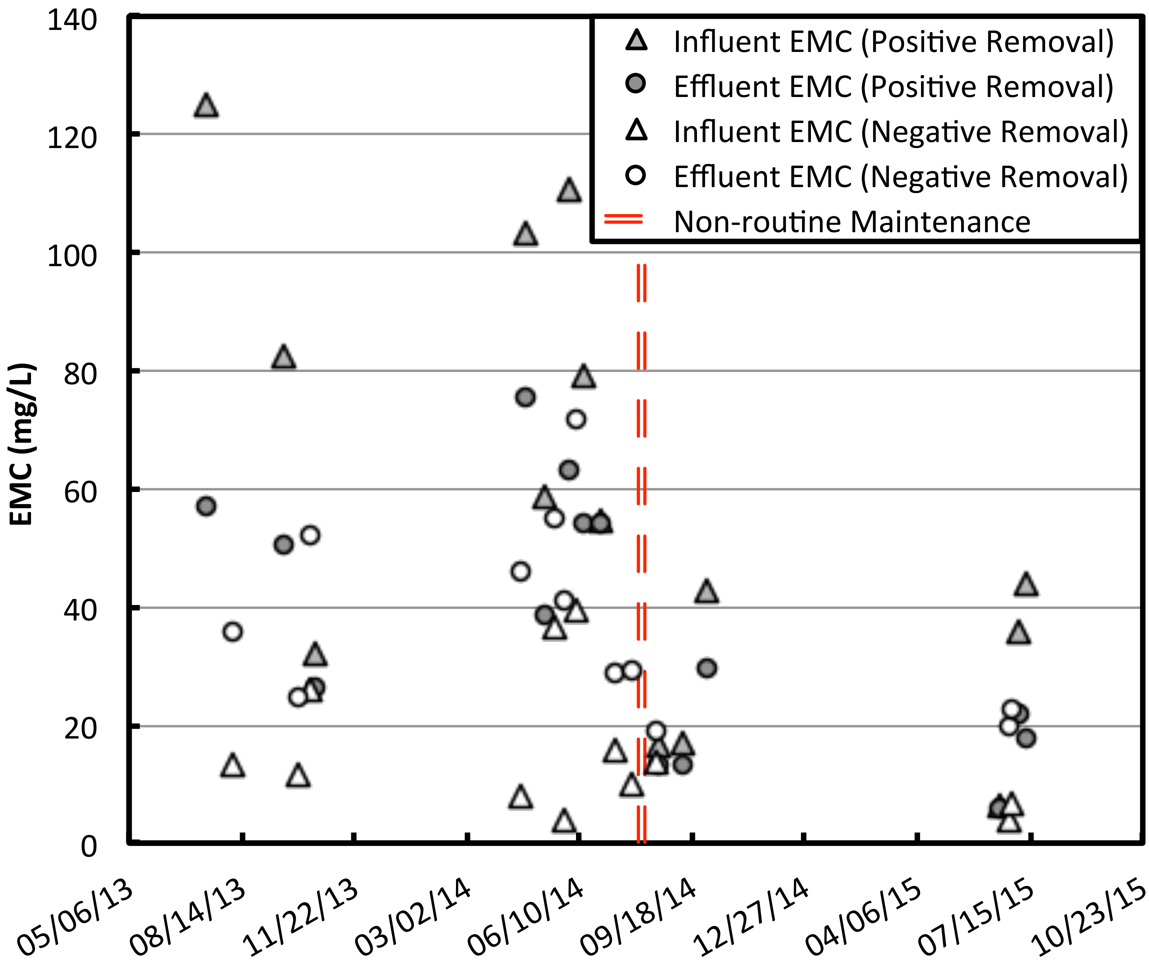


Figure 14. Influent and effluent event mean phosphate concentrations.

To isolate and investigate the performance of the IESF trench after the August 2014 non-routine maintenance, events 21 through 28 were grouped and the performance over this span of events was determined. This grouping does not include the first event after maintenance (i.e., event 20), which was considered a rinse event (see above). Table 4 summarizes influent and effluent mass loads corresponding to these events and gives the overall mass load retention. The overall mass load retained was 43%, which is slightly less than the corresponding value for all 2015 events. This appears to be due to the low influent concentrations experienced after non-routine maintenance in 2014, as low influent concentration events typically have lower retention rates as per the discussion above.

Table 4. Summary of events after August 2014 non-routine maintenance. (Excludes Event 20 as described above).

Event	Mass P In (g)	Mass P Out (g)
21	5.9	4.7
22	0.7	0.5
23	6.7	4.7
24	0.0	0.0
25	0.9	4.8
26	0.2	0.6
27	47.4	29.3
28	52.7	21.1
Total =	**115**	**66**
Percent Retained =	**43%**	

Maintenance

As with any stormwater control measure, visual inspection and maintenance of IESF trenches is imperative for the practice to remain functional and operate optimally for extended periods (Erickson et al. 2013). This monitoring study showed the necessity and impact of routine and non-routine maintenance on IESF trenches. Routine maintenance occurs on a regular, relatively frequent schedule (Erickson et al. 2013) and for this project included inspection, weeding, raking, and breaking up iron clumps. Non-routine maintenance occurs only as required by a change (often reduction) in performance, and thus occurs on an irregular, often infrequent schedule (Erickson et al. 2013). Non-routine maintenance was only performed once on this IESF trench between January 2011 (installation) and September 2015, and occurred in August 2014. A summary of routine and non-routine maintenance activities performed on the IESF trench along with the corresponding date are shown in Table 5. To more readily observe the performance of the IESF trench before and after maintenance, these activities are also shown in chronological order in Table 3.

Table 5. Routine and non-routine Maintenance activities performed on the IESF trench.

Date	Maintenance Completed
7/19/2013	Weeded and raked filter
7/22/2013	Weeded and raked filter
5/22/2014	Weeded and raked filter
7/25/2014	Raked filter
8/5/2014	Removed solids from surface, raked, tilled filter. Broke up iron clumps (up to ~12" long)
6/1/2015	Broke up iron clumps (2-4" across)

During runoff events, water carried duckweed, algae, and other vegetation from the pond onto the filter surface. As water passed through the filter and water levels in the pond decreased, this vegetation was deposited on the filter surface. Routine maintenance was therefore undertaken to remove the effects of deposition onto the pond surface. Routine maintenance activities included pulling vegetation (i.e., weeds) that were growing on the filter surface and raking the filter surface. Raking refers to disturbing the surface of the filter to a depth of 1-3" with a metal rake. This was often enough to break through any minor "crust" of iron/sand, and allowed water to flow through the media. Often, if the filter was submerged, there was a release of bubbles associated with this raking. Sometimes raking was completed when the filter was not submerged; this was done to break up the surface and remove any crust, and also to loosen up any vegetation growing on the surface. Raking was by far the most efficient means of removing smaller weeds from the filter surface (vs. pulling by hand). It is unclear from the data what effect routine maintenance had on the phosphate removal performance of the IESF trench, though field observations confirmed that routine maintenance preserved or restored adequate hydraulic (i.e., flow through) performance. Appendix A lists design suggestions that attempt to minimize the deposition of vegetation on the filter surface.

During Spring and early Summer of 2014, the filter began to filter water much more slowly such that it would remain submerged for days following a rainfall/runoff event. This is not desirable for at least two reasons: 1) water storage volume in the pond was unavailable for subsequent rainfall events, and 2) the filter must be able to dry as this prevents anaerobic conditions from developing and allows the iron to rust, the latter of which creates more phosphate adsorption sites. Visual inspection of the filter revealed solids had accumulated on or in the top portion of the filter media. These solids were in the form of duckweed and algae on the surface of the filter and a grey muck layer at or near the surface of the filter at some locations (Figure 15 and Figure 16). In some locations the grey muck was observed two to three inches below the surface.

Figure 15. Surface of the IESF trench showing accumulated grey muck.

Thus, in an attempt to improve flow through the filter, non-routine maintenance was performed in August 2014 and included scraping and removing algae from the filter surface, removing as much of the grey muck as possible, breaking up the sand media to a depth of several inches with metal rakes, and breaking up large clumps of iron shaving conglomerates (some 12" or more in their longest dimension) with a sledgehammer. Iron clumps of this size tended to be isolated, relatively deep (4-8 inches below the surface), are nearly impermeable, but scattered throughout the filter media and therefore likely have minimal impact on the hydraulic performance of the IESF trench. Iron clumps may reduce iron-water contact because large particles have less contact area than smaller particles. This non-routine maintenance required approximately 4 hours for one stormwater professional and 8 hours of labor for three hourly staff, who used shovels and steel rakes to disrupt, dislodge, and remove material as described above, sledgehammers to break up large iron clumps, and buckets to transport material that was removed from the filter surface.

One of the primary purposes of this non-routine maintenance was to remove a layer of grey muck (see Figure 15 and Figure 16) that was observed near and just below the surface of the filter. It is hypothesized that the grey muck was gleyed sand, which is iron-rich sand that has been reduced to ferrous iron due to anaerobic conditions from prolonged water saturation. Gleyed soils exhibit a similar appearance and texture as the grey muck that was observed at (and removed from) the site. The grey muck may have also contained decomposing organic matter may have developed as a result of prolonged water saturation caused by the intense precipitation conditions observed in June 2014 (previously discussed), the accumulation of fine organic material at or just under the surface of the filter from four previous rainy seasons, or both. It is important to note that grey muck has not been observed at any of the other IESF trenches within the City of Prior Lake.

Figure 16. Sand-iron media taken from the filter (left) and grey muck (right).

The non-routine maintenance activities immediately improved hydraulic performance (i.e., increased filtration rates) and, after what appeared to be a rinse of the filter by the first runoff event after non-routine maintenance, improved phosphate retention as previously discussed.

Non-routine maintenance actions on other IESF trenches in the City of Prior Lake were often required to improve hydraulic performance. The non-routine maintenance performed on other trenches did not include removing grey muck (not observed at any other sites), but did include vigorous raking with a steel rake to break up iron-rich "crusts" that formed over the entire surface of the IESF trench. These crusts, often 0.5 – 1.5 inches thick, were impermeable and prevented the trench from filtering stormwater. Once broken, air bubbled through any standing water and hydraulic performance was restored. These other trenches, however, have not been assessed for phosphate retention so the impact of non-routine maintenance on this aspect of performance has not been evaluated. It is assumed, however, that IESF trenches that filter stormwater perform better than trenches that are sealed with an impermeable crust and do not treat any stormwater.

The City of Prior Lake has observed iron clumping in this and other IESF trenches since 2012, one year after construction. Observations by the City of Prior Lake on all of their IESF trenches have also revealed that iron clumping (though not grey muck) is more prevalent on IESF trenches that have been submerged for extended periods, as was observed in the IESF trench that has been monitored for this project. This may occur as a result of large storm events (or multiple events over a short time period) that take an extended length of time to drain (greater than 48 hours) or if the surface is intermediately clogged by vegetation or organic material (often alleviated by routine maintenance). The filter surface is lower near the south end of the filter studied in this project, and thus this area is often wet compared to the rest of the filter. Clumping of iron has also been observed in this area in 2015. As previously mentioned, the iron clumps are scattered throughout the media and will not likely reduce flow through the filter. Clumping may, however, reduce iron-water contact because large particles have less contact area than smaller particles.

Routine maintenance was performed throughout this project and was scheduled based on visual inspection of the site. As recommended by Erickson et al. (2013), visual inspection should occur at least annually for every site and can be used to schedule routine, non-routine, and major maintenance. For this project, visual inspection and (a decrease in) hydraulic and phosphate removal performance were used to schedule non-routine maintenance for the site.

Flow Volume Exceedance Plot

As described by Erickson et al. (2013), influent flow exceedance plots are graphical representations of the performance of a stormwater treatment practice as a function of influent flow volume and/or percent exceedance of the influent flow volume. Data is plotted from multiple events as influent-effluent pairs (e.g., influent mass P load and effluent mass P load from the same event) as a function of the percent influent volume exceedance. Percentiles are a common statistical representation of data, and are related to percent exceedance by Equation 4:

$$\text{Percent Exceedance} = 1 - \text{Percentile} \tag{4}$$

For example, the 75th percentile (0.75) represents the point at which 75% of the data is smaller and 25% of the data is larger. This same data point corresponds to the 25% exceedance because 25% of the data exceed this value and 75% of the data do not exceed (i.e., are smaller). One advantage of percent exceedance compared to percentiles is that most often stormwater managers are interested in the values that exceed a certain criterion, standard, or goal. For example, if a water quality goal is 40 μg/L, the percent exceedance method allows for quick determination of which storms, if any, exceed this goal.

The influent and effluent flow volume in this project are identical, so the exceedance plots shown are based on flow volume. The flow volume exceedance plot is shown in Figure 17, which illustrates the percent of storms that exceed a specific flow volume. To create this plot, the flow volume for all 28 storm events is ranked from smallest to largest, and plotted as a function of percent exceedance (also called a flow duration curve). The largest storm has zero percent exceedance because no storms are larger (i.e., exceeded). The smallest storm has nearly 100% exceedance because all storms are larger. Similarly, each storm is exceeded by a certain percentage of the storms measured. For example, Storm Event 12 had a flow volume of 635,323 L (Table 2). Approximately 40% of the measured storms are larger than Storm Event 12 (0.635 Million Liters) because 40% on the horizontal axis corresponds to 0.635 Million Liters on the vertical axis.

An advantage of the flow exceedance plot is that the relationship between flow volume (i.e., storm size) and performance (or other plotted characteristics) can be observed. For this study (Figure 17), one can define "large" storms as the largest 25% of storms (0 – 25% exceedance); "small" storms as the smallest 25% of storms (75 – 100% exceedance); and medium storms as storms around the median (25 – 75% exceedance). From Figure 17, large storms are storms with rainfall depths of approximately 1.5 inches or larger and flow volumes of 1.2 x 10^6 L or more. Small storms have rainfall depths of approximately 0.25 inches or smaller and flow volumes of 0.14 x 10^6 L or less. Finally, medium storms have rainfall depths between 0.25 and 1.5 inches and flow volumes between 0.14 x 10^6 L and 1.2 x 10^6 L. It's important to note that approximately 75% of the cumulative flow volume that passed through the IESF trench during this monitoring study (2013 – 2015) was contributed by large storms.

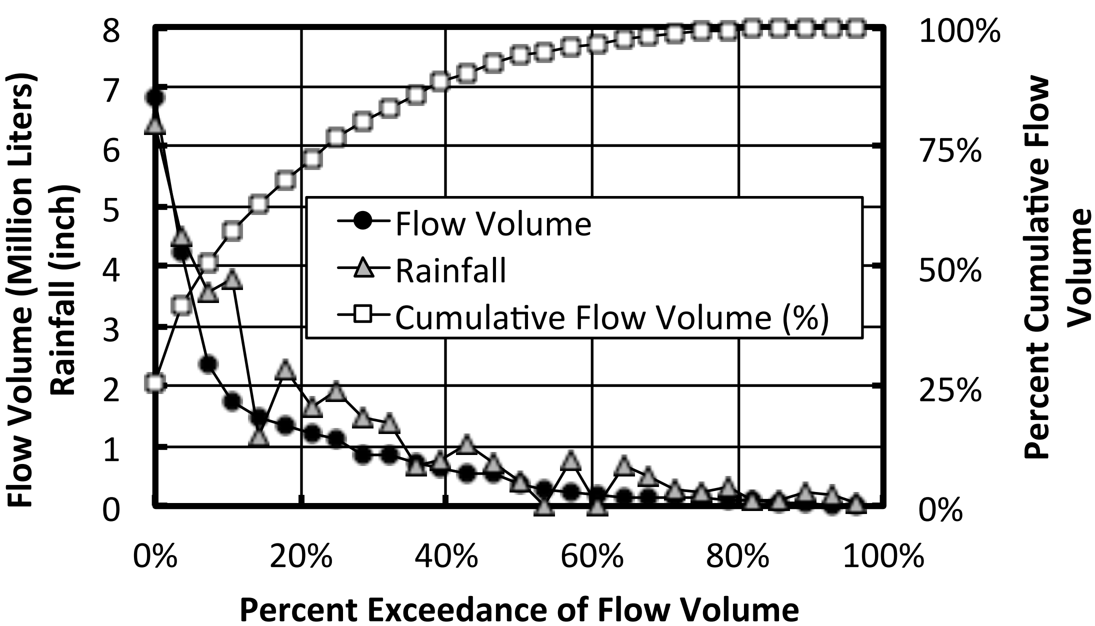
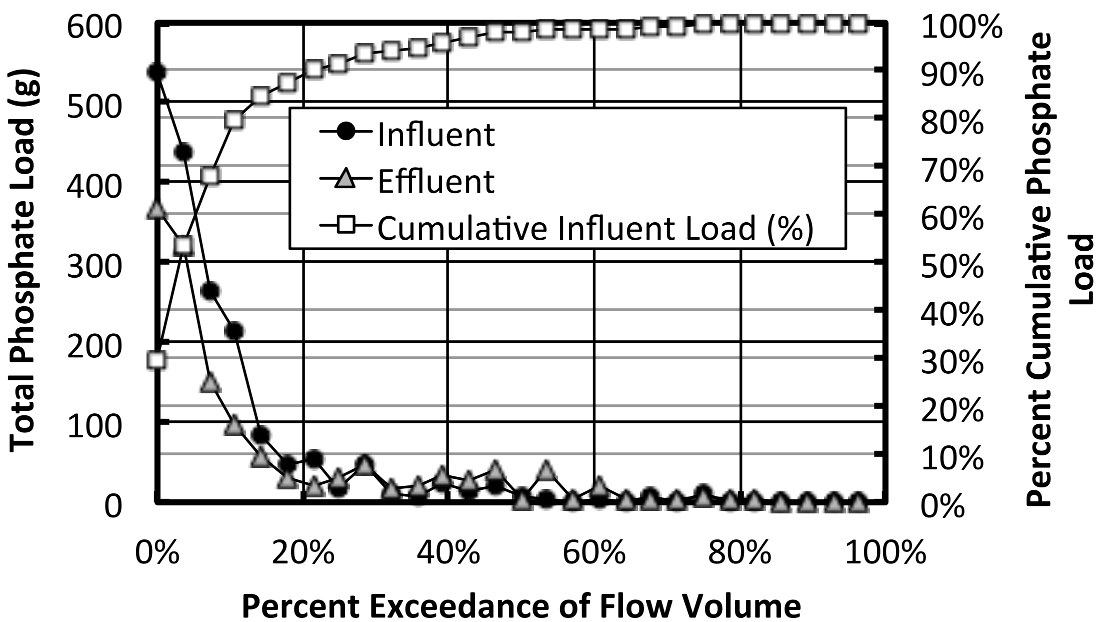
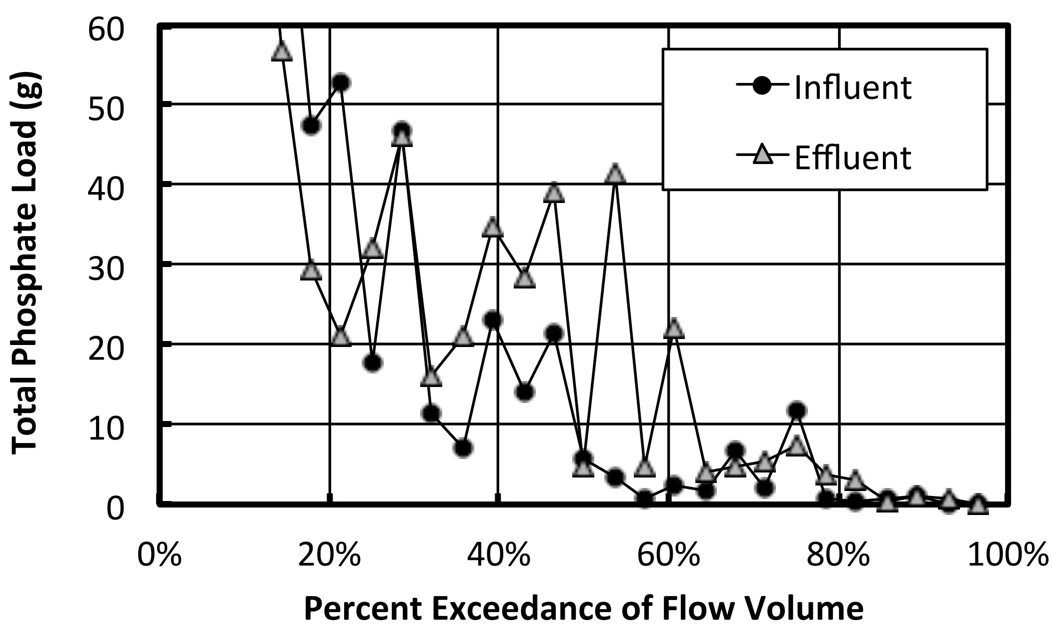


Figure 17. Flow volume exceedance plot.

The total phosphate load exceedance plot is shown in Figure 18. In this figure, when the influent line is above (i.e., greater than) the effluent line, the trench is providing positive phosphate removal (influent mass load > effluent mass load). When the order is reversed and the effluent line is above the influent line, this indicates negative removal (influent mass load < effluent mass load). Several observations can be made from Figure 18: 1) the seven largest storms all exhibited positive removal, 2) the seven largest storms represent 25% of the storms measured (7 out of 28) and would be considered large storms as described above, and 3) 90% of the influent phosphate load was contributed by these seven storms. This indicates that these large storms contributed 75% of the flow volume, 90% of the influent phosphate load, and resulted in nearly all of the phosphate load reduction. These large storms also had the highest influent event mean concentration, which is believed to be the primary reason that positive removal was observed.



A.



B.

Figure 18. Total phosphate load exceedance plot for (A) all storms and for (B) storms contributing less than 60 g.

Conclusions

The IESF trench at Prior Lake achieved an overall 26% phosphate retention over 28 monitored events spanning 2013-2015. The phosphate retention in 2013 (8 events) was 18%, in 2014 (15 events) the retention was 25%, and in 2015 (5 events) the phosphate retention was 45%. Large events had the highest influent event mean concentration, contributed 75% of the flow volume, 90% of the influent phosphate load, and resulted in nearly all the phosphate load reduction. Small and Medium storms (rainfall < 1.5 inches; flow volumes < 1.2×10^6 L) contributed the remaining flow volume and influent phosphate load, and provided minimal or negative phosphate removal.

Maintenance, both routine and non-routine, of the IESF trench is critical. In July 2014 the trench became clogged with a grey muck that is suspected to be gleyed sand and to possibly contain organic matter. Due to clogging, filtration rates decreased such that, after a rainfall event, the filter surface was submerged for several days. Phosphate removal achieved by the trench also decreased at this time to negative values. Non-routine maintenance was performed in August 2014 and included scraping and removing algae from the filter surface, removing grey muck from the top 1 – 3 inches, breaking up the sand media to a depth of several inches with metal rakes, and breaking up large clumps of iron shaving conglomerates into pebble-sized particles with a sledgehammer. After this non-routine maintenance, filtration rates increased and, after an initial rinse from the next runoff event, the phosphate retention achieved by the trench substantially increased.

Products

This report represents the primary product and final deliverable under this contract and includes a description of the work completed, design recommendations, and data collected. As mentioned previously, Appendix B shows rainfall-runoff relationships and "pollutographs" (concentration versus time) for each event listed in Table 2. As requested, an electronic summary of all data for the EQuIS database has also been provided. This report and the recommendations provided herein are Design Standards for Iron Enhanced Filtration Trenches associated with Wet Retention Ponds.

Photos

Several photos are provided in this section to show the IESF trench studied as part of this project. Some photos have been submitted as separate files with this Final Report.

Figure 19: March 1, 2012 (looking South). Ice cover melting over IESF Trench. Approximately one year after construction.

Figure 20: March 6, 2012 (looking South). IESF draining spring snowmelt.

Figure 21: March 15, 2012 (looking North). IESF clear of ice and water level below filter surface.

Figure 22: March 15, 2012 (looking South). View of pond cell adjacent to IESF.

Figure 23: April 24, 2012 (looking South). IESF surface prior to rainfall event.

Figure 24: May 9, 2012 (looking South). IESF trench shortly after storm event. Water level above trench surface and passing through the IESF.

Figure 25: May 9, 2012 (Looking North). IESF trench shortly after storm event.

Figure 26: August 16, 2012 (looking south). Pond outlet control structure grate (foreground) and IESF Trench (background).

Figure 27: August 4, 2014 (looking South). Non-routine maintenance; raking algae and vegetation.

Figure 28: August 4, 2014. Non-routine maintenance; Iron Clumps found while raking.

Figure 29: August 4, 2014. Non-routine maintenance; raking revealed grey muck layer that prevented flow through the IESF trench.

Figure 30: August 4, 2014. Non-Routine Maintenance. Grey muck layer near the surface.

Figure 31: August 5, 2015 (looking South). View of the IESF at the end of the project.

Figure 32: August 5, 2015 (looking North). View of IESF and low spot where stormwater first enters the trench during a storm event

Figure 33: August 5, 2015 (looking North).

Public Outreach and Education

Public outreach and education were Objective 4 of the project. A brief summary is provided here.

Partnerships have been established with the Minimum Impact Design Standards (MIDS) team and others for the review and dissemination of knowledge gained. Two meetings (3/23/2011 & 4/6/2012) of a technical advisory committee were held to make sure that the project met the needs of the practicing community.

Results will be disseminated in an upcoming edition, subsequent to this final report, of UPDATES, an email stormwater newsletter distributed to more than 2400 subscribers. Twenty presentations have included the conceptual design of IESF trenches as installed in Prior Lake and have communicated the ability of iron enhanced sand filtration to retain phosphate. It is estimated that these efforts have reached over 1000 participants. Website links are provided to access copies of the UPDATES newsletter (http://stormwater.safl.umn.edu/updates-newsletters) and full presentations (http://stormwater.safl.umn.edu/presentations), where available. The presentations that correspond to this project include:

1. "Removing Dissolved Pollutants from Stormwater," Andrew J. Erickson and John S. Gulliver (Presentation by AJ Erickson), Minnesota Association of Watershed Districts, Alexandria, MN, December 2, 2010.

2. "Application of Iron Enhanced Sand Filtration: The Minnesota Filter." A. J. Erickson and J.S. Gulliver (Presentation by A.J. Erickson), *Vermillion River Technical Advisory Group*. Apple Valley, MN, March 9, 2011.
3. "Innovation in Stormwater Treatment," *Spring 2011 Williams Memorial Lecture*, Water Center & School of Natural Resources, University of Nebraska, Lincoln, NE, March 30, 2011.
4. "Performance and maintenance of Retrofit Stormwater BMPs," A.J. Erickson and J.S. Gulliver (Presentation by A.J. Erickson) *2011 Minnesota Erosion Control Association's Conference*, Bloomington, MN, March 4, 2011.
5. "Plusses and Minuses of Stormwater Treatment Trains," National Association of County Engineers 2011 Conference, Minneapolis, MN, April 18 – 20, 2011.
6. "Unit Processes in Stormwater Treatment and Innovations Thereof," *Seminar Series, Department of Civil and Environmental Engineering*, University of California-Loa Angeles, Los Angeles, CA, April 26, 2011.
7. "Innovations in Stormwater Treatment," Water Resources Science Seminar Series, University of Minnesota, February 3, 2012.
8. "Binding phosphorus in stormwater, lakes, rivers and streams," PICKM Alliance Coalition of Lake & River Associations, Pokegama Lake, MN, October 25, 2012.
9. "Gismos for Stormwater Treatment," John S. Gulliver, Presentation to the Carnegie Mellon University Student Chapter of the Environmental and Water Resources Institute, Pittsburgh, PA, June 13, 2014.
10. "Gismos for Stormwater Treatment," John S. Gulliver, Presentation to the Villanova Center for the Advancement of Sustainability in Engineering, Villanova University, Villanova, PA, July 14, 2014.
11. "Current and Unfolding LID and Stormwater BMP Research at the University of Minnesota," Minnesota Water Resources Conference, St. Paul, MN, October 14-15, 2014.
12. "Capturing Dissolved Pollutants from Stormwater," A.J. Erickson, J.S. Gulliver and P.T. Weiss (Presentation by A. Erickson), *2011 Minnesota Water Resources Conference,* St. Paul, MN October 18-19, 2011.
13. "Improving Stormwater Projects to Capture Dissolved Pollutants," A.J. Erickson, E. Anderson-Wenz, J.S. Gulliver, (Presentation by A.J. Erickson) *2013 International Low Impact Development Symposium*, Saint Paul, Minnesota, August 18-21, 2013.
14. "Improving Stormwater Projects To Capture Dissolved Pollutants," A.J. Erickson, J.S. Gulliver, W.A. Arnold (Poster Presentation by A.J. Erickson), *Environmental Engineers and Scientists of 2050: Education, Research, and Practice*, Denver, CO, July 14 – 16, 2013.
15. Erickson, A.J., J.S. Gulliver and P.T. Weiss, "Capturing Dissolved Phosphorus With Iron-Enhanced Sand Filtration," *StormCon 2010*, August 1 – 4, 2010, San Antonio, TX.
16. Erickson, A.J., J. S. Gulliver, and P.T. Weiss, "Capturing dissolved pollutants from stormwater," *International Conference on Stormwater and Urban Water Systems Modeling*, February 24 – 25, 2011, Toronto, Canada.
17. Erickson, A.J., P.T. Weiss and J.S. Gulliver, "Removing dissolved pollutants from stormwater," *StormCon 2011,* August 22 – 26, 2011, Anaheim, CA.
18. Erickson, A. J., J. S. Gulliver and P. T. Weiss, "Removing Dissolved Phosphorus from Stormwater," *12th International Conference on Urban Drainage*, Porto Alegre/Brazil, 11-16 September 2011.

19. Erickson, A.J., J.S. Gulliver and P.T. Weiss, "Field Results for Iron Enhanced Sand Filtration System," *2013 World Environmental and Water Resources Congress*, Cincinnati, OH, May 19-23, 2013.

Results were, and will continue to be incorporated into Stormwater 'U' courses and workshops. Results have already been included in senior and/or graduate urban hydrology classes at the University of Minnesota and Valparaiso University, Valparaiso, IN.

Long-term Results

Technical Impact

The experience gained from this project has led to the following lessons learned regarding the installation and long-term performance of IESF trenches:

1. Iron enhanced sand filter trenches can reduce overall phosphate mass loads to receiving water bodies. Most of the mass load reduction is achieved during large rainfall events with high influent concentrations. At low influent concentrations, however, the IESF trench may provide less (and sometimes negative) removal of phosphate.
2. Maintenance, both routine and non-routine, is critical to the performance of an IESF trench.
    a. Routine maintenance consisted of inspection, weeding, raking, and breaking up iron clumps and occurred throughout the life of the IESF trench and the project. Routine maintenance reduced the need for non-routine maintenance. Routine maintenance was required approximately every 2-4 weeks and required approximately four hours for hourly staff per visit from April through October, each year. This is approximately 40 hours for hourly staff per year.
    b. Non-routine maintenance was required once at the site in August 2014; four years after construction and one month after several significant rainfalls, which kept the trench wet for an extended period of time. Non-routine maintenance included scraping and removing algae from the filter surface, removing as much of the grey muck as possible, breaking up the sand media to a depth of several inches with metal rakes, and breaking up large clumps of iron shaving conglomerates (some 12" or more in their longest dimension) with a sledge hammer. This non-routine maintenance required approximately 4 hours for one stormwater professional and 24 hours of labor for hourly staff, who used shovels and steel rakes to disrupt, dislodge, and remove material, sledgehammers to break up large iron clumps, and buckets to transport material that was removed from the filter surface.
3. Non-routine maintenance substantially improved performance as evidenced by positive removal occurring at lower influent phosphate concentrations.
4. Future IESF trench designs could include a barrier or surface skimmer around the perimeter of the trench so that floating algae is not allowed onto the surface of the filter

(see Appendix A for more details and recommendations). Limiting the deposition of organic material onto the surface of the filter will reduce the routine (and non-routine) maintenance burden.

5. If clumps of iron shavings develop, breaking up the clumps into small pieces (as small as practically possible) is recommended. Although these clumps do not reduce overall permeability, breaking up the clumps should allow the iron to become more dispersed in the sand and will increase the surface area available for phosphate adsorption (i.e., removal).
6. The IESF trench should be allowed to dry out between rainfall/runoff events. When the filter is allowed to dry, the iron within the filter will rust, which will form more phosphate adsorption sites and increase the longevity of the filter. If this does not occur, the trench, or parts of the trench, may become anaerobic and iron shavings may clump together and form large conglomerates of iron or gleyed sand (grey impermeable muck). These conglomerates do not appear to reduce permeability but are theorized to reduce the effectiveness of the filter due to less iron surface area. Prolonged inundation may also result in iron "crust" that is impermeable and can reduce permeability to near zero. Also, anaerobic conditions may lead to the presence of anaerobic bacteria and filter clogging.

Partnerships and Alliances

This project would not have been possible without the partnership between the Minnesota Pollution Control Agency, City of Prior Lake, the University of Minnesota St. Anthony Falls Laboratory, the Prior Lake Spring Lake Watershed District, and the Scott (County) Watershed Management Organization (Scott WMO). With regards to the current project (and other IESF trenches installed by the City of Prior Lake), the relationships developed as a result of this project will be maintained and communications, discussions, and efforts to better understand IESF trenches and their requirements will continue. This will help optimize the performance of current and future systems. Although no specific new projects are planned at this time, this project has formed relationships between these entities that will encourage future stormwater management projects.

Without additional funding, continuation of this project at the level described in this report is not likely. In the future, however, grab sampling and/or periodic monitoring may occur because the City of Prior Lake will likely need to assess the long-term performance of the IESF trench and when non-routine maintenance is necessary.

Sharing of Results

Results of this project, technology transfer, and dissemination was accomplished as previously described in the Work Plan Review section, Objective 4 and the Public Outreach and Education section, above. Watershed planners, municipal engineers, and consulting environmental or stormwater engineers would be interested in the results of this project.

Final Expenditures

The project was completed on time and within budget. The Final Expenditures can be found in a separate spreadsheet document listing individual Objectives, Tasks, and line items categories.

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Appendix A – Design, Operation, and Maintenance Recommendations

Design

Several research projects and field installations of iron enhanced sand filters (IESF) have occurred in Minnesota since 2003. Some of these studies and projects were used in the development of the IESF trenches installed in the City of Prior Lake, MN. Past work, this monitoring study, and experience gained from the City of Prior Lake's design and construction of several IESF trenches have led to the following recommends for future IESF trenches:

- Clean, washed sand meeting ASTM C33 specifications shall be used for the IESF trench media.
- The iron enhanced sand portion of the media shall be approximately 18 inches thick. Shallower depth filters are acceptable, but may not perform as well or last as long.
- The iron enhanced sand media shall contain 5 – 8% iron shavings by weight mixed thoroughly throughout the entire media volume.
- The iron enhanced sand media shall be covered by at least 3 inches of ASTM C33 sand. Non-routine maintenance shall include periodically removing 1 to 1.5 inches of this layer, and replacing with clean washed ASTM C33 sand.
- The IESF shall have a layer of clean washed ASTM C33 sand of at least 6 inches thick, below the iron enhanced sand media.
- The IESF media should be contained in an impermeable barrier on all sides except the top.
- In order to prevent duckweed, algae, and other organics or solids from accumulating on the surface of the filter, the filter should be surrounded by an impermeable barrier, surface skimmer, or the design should incorporate a separate pretreatment cell containing only sand that discharges to the IESF trench (if space allows). The top elevation of the barrier should be higher than the water level control weir crest in the catch basin (Figure A1) so that the flow will not overtop the weir surrounding the filter during the design event. In order to allow pond water to flow onto the filter, a pipe should run from the pond (at a depth below the frost line) through the impermeable weir to the surface of the IESF trench. A flow spreader or manifold system may be necessary to evenly distribute the water over the entire surface of the filter. The barrier, pipe, and elevations should be designed such that the intended treatment volume and routing are as intended, and structural integrity is protected. See Figure A1.
- Stormwater should enter the IESF evenly, and be distributed across the entire surface to ensure widespread treatment and minimize the occurrence of small areas treating an unequal portion of the stormwater. Earthen berms and grading have been found to be imprecise, resulting in low areas that receive considerably more stormwater compared to the entire filter surface. A level spreader and manifold distribution system may be appropriate or necessary.

- Underdrain size should be considered during design. All sites in Prior Lake were designed and installed with 4” perforated underdrains. The flow rate for some sites appears to be limited by this pipe size, which results in longer drawdown times and the potential for anaerobic conditions. Larger underdrain pipes could be used to avoid limiting the flow rate with the underdrain. If the flow rate is found to be too large such that performance is limited by contact time, a cap with an orifice smaller than the pipe could be added to the underdrain outlet.

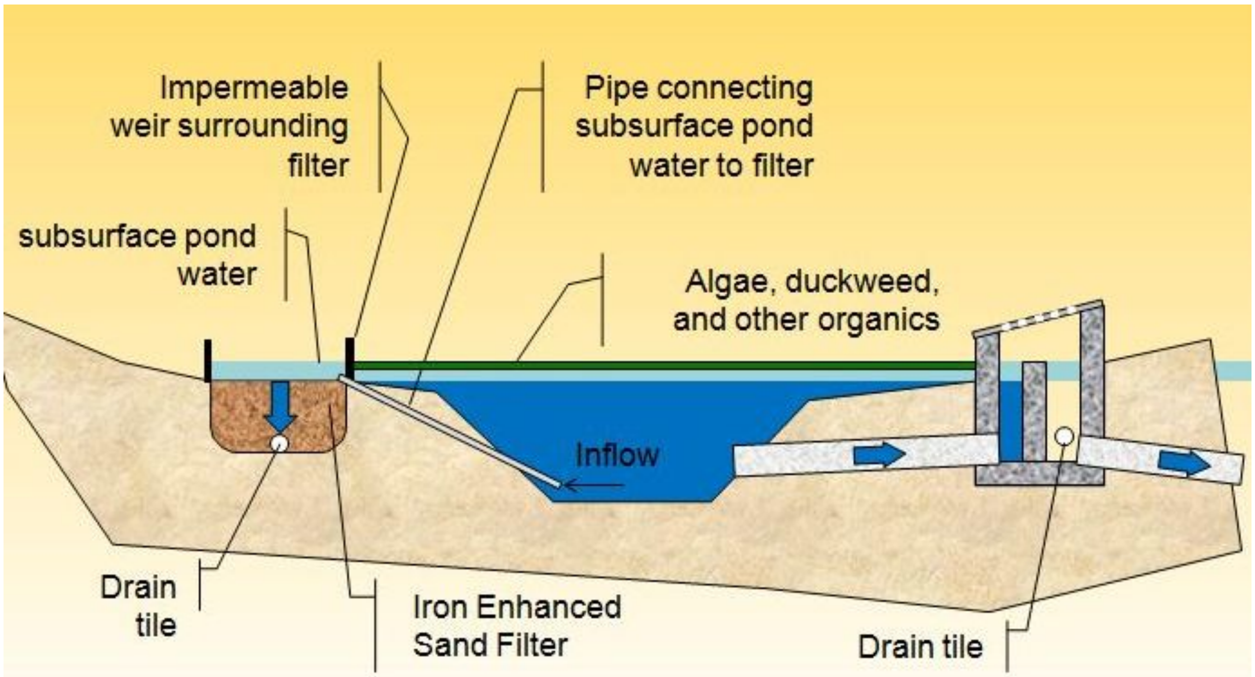

Figure A1. Schematic showing impermeable weir around filter.

Operation and Maintenance

Based on the experience gained during the course of this project, the following recommendations regarding operation and maintenance will enhance performance and increase the life of an IESF trench.

- Routine maintenance (~4 times a year) of the IESF involves removing weeds and other vegetation growing on the surface of the filter and raking the filter to break up the surface. Non-routine maintenance (~ 1 time per year) may include 1) removing the top 1 to 1.5 inches of sand and accumulated solids/organics that have been filtered and replacing with clean washed sand, and 2) breaking up clumps of iron shaving conglomerates (if present).
    - If iron-sand media is at the surface, iron clumps may be visibly apparent at or near the surface. Iron clumps are conglomerates of iron and sand, usually 1 cm in diameter or more, as shown in Figure 16 and Figure 28.
    - If clean sand is at the surface, the subsurface should be probed for iron clumps with a steel rake.

    - Once iron clumps are found, a hammer or sledgehammer should be used to crush the iron clumps to pebble-size (~ 1 cm diameter) or smaller.
- The filter must be allowed to dry between rainfall events. This will prevent the development of anaerobic conditions and will allow more phosphate adsorption sites to develop on the iron shavings (see Technical Impacts for possible design solutions). Also, iron clumping appears to be more prevalent when the filter remains submerged for extended periods (i.e., more than two days).

Appendix B - Event Data

Two sets of graphs, "Rain and Pond Level" and “Pollutographs” (concentration versus time), have been provided for all events in the following graphs. The first, Rain and Pond Level, includes the 5-minute rainfall and cumulative rainfall distributions (primary axis), as well as the pond water level elevation (secondary axis). The Pollutographs include the flow rate (primary axis), and the influent and effluent dissolved phosphate concentrations (secondary axis).

Influent sample collection was time-based, and thus could not be combined into a composite sample (Erickson et al. 2013). Therefore, influent samples appear as individual sample concentrations (i.e., dots). Note that some influent samples appear as horizontal lines (see Figure B1, from 7/18/13 through 7/19/13) because long duration events filled all sample bottles. Horizontal lines were used to indicate that the no new samples were collected during this period. Sampling resumed when samples were retrieved and samplers were reset, as indicated by influent samples appearing as individual concentrations.

Effluent sample collection was flow-based, and thus individual samples could be combined into a single composite sample (Erickson et al. 2013) for most events. Effluent samples that were combined before analysis yielded a single concentration for the duration of effluent sampling, which is equivalent to the Event Mean Concentration (Erickson et al. 2013). In these cases, the effluent phosphate EMC appears as a horizontal line on the pollutograph, as shown in Figure B1. Some events filled all effluent sample bottles, requiring retrieval of sample bottles and resetting of automatic samplers. For these events, multiple horizontal lines are shown for effluent phosphate concentrations.

In the pollutographs, when the influent concentration line is above (i.e., greater than) the effluent line, the trench is providing positive phosphate removal (influent concentration > effluent concentration). When the order is reversed and the effluent line is above the influent line, this indicates negative removal (influent concentration < effluent concentration).

For events 3 through 6, valid rainfall data was not obtained due to rain gage errors. If possible, nearby rainfall daily amounts were obtained from Weather Underground (http://www.wunderground.com/). For event 4, no rainfall was recorded at any nearby rain gauge. Thus, the rainfall depth for that event is listed as "unknown." Also, for event 25, the ground wire from the influent sampler to the data logger was disconnected, resulting in the collection of more influent samples by the sampler (24) than were recorded by the data logger (16). Due to the fact that there was no method to determine what samples were the extra samples, the average phosphate concentration of all 24 bottles was used as the concentration of each of the 16 bottles recorded by the data logger and used in analysis. With an average influent concentration of the 24 bottles of 3.7 μg/L (range 2.0 to 6.2 μg/L) and a standard deviation of 0.7 μg/L, any error associated with this method was deemed acceptable.

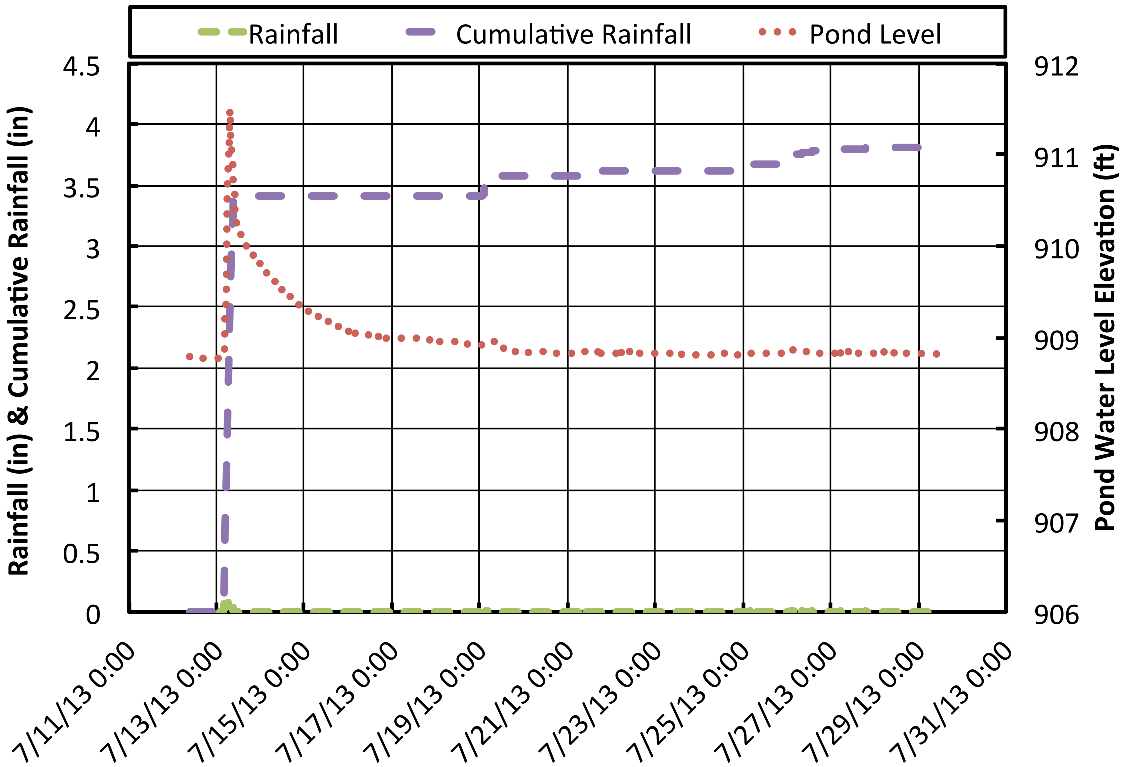

Figure B1. Rain and pond level for event 1.

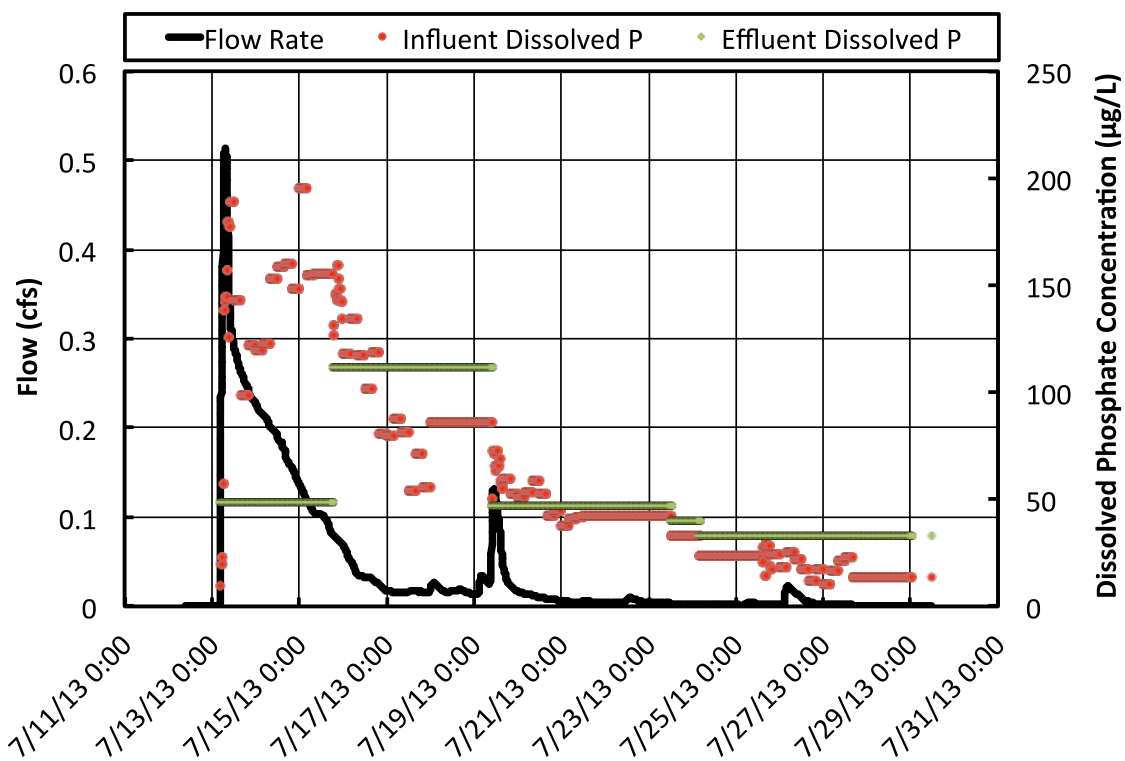

Figure B2. Flow and Pollutograph for event 1.

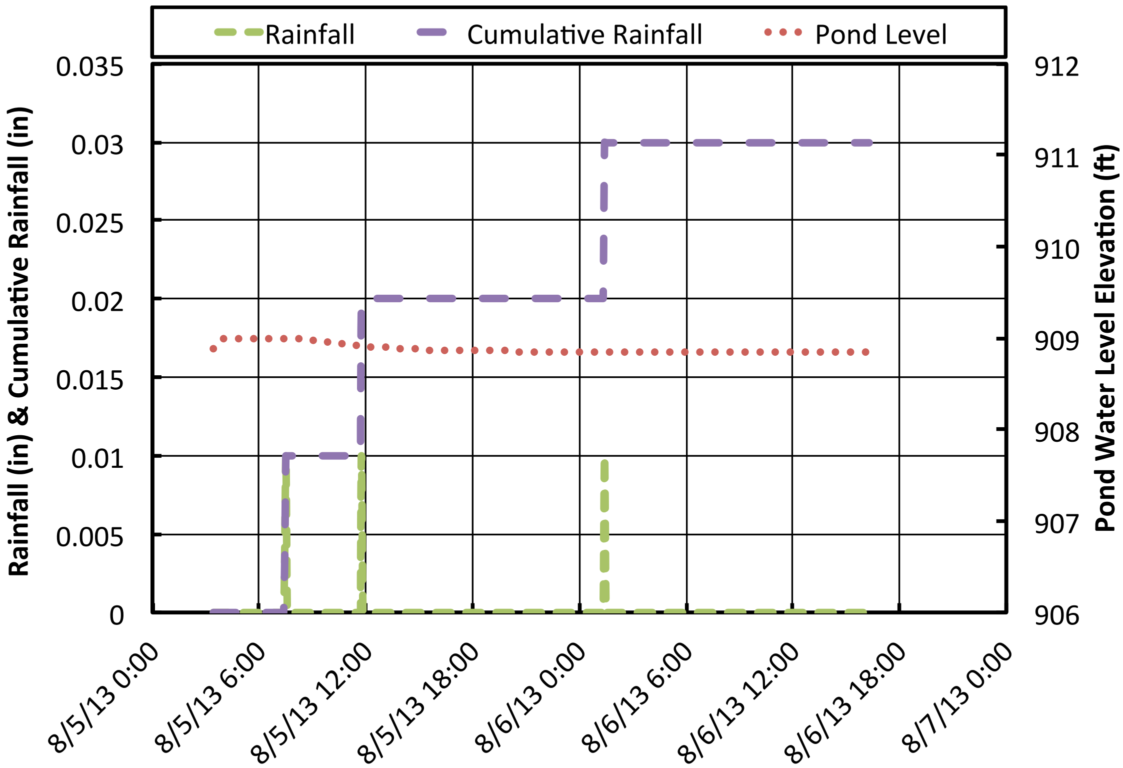

Figure B3. Rain and pond level for event 2.

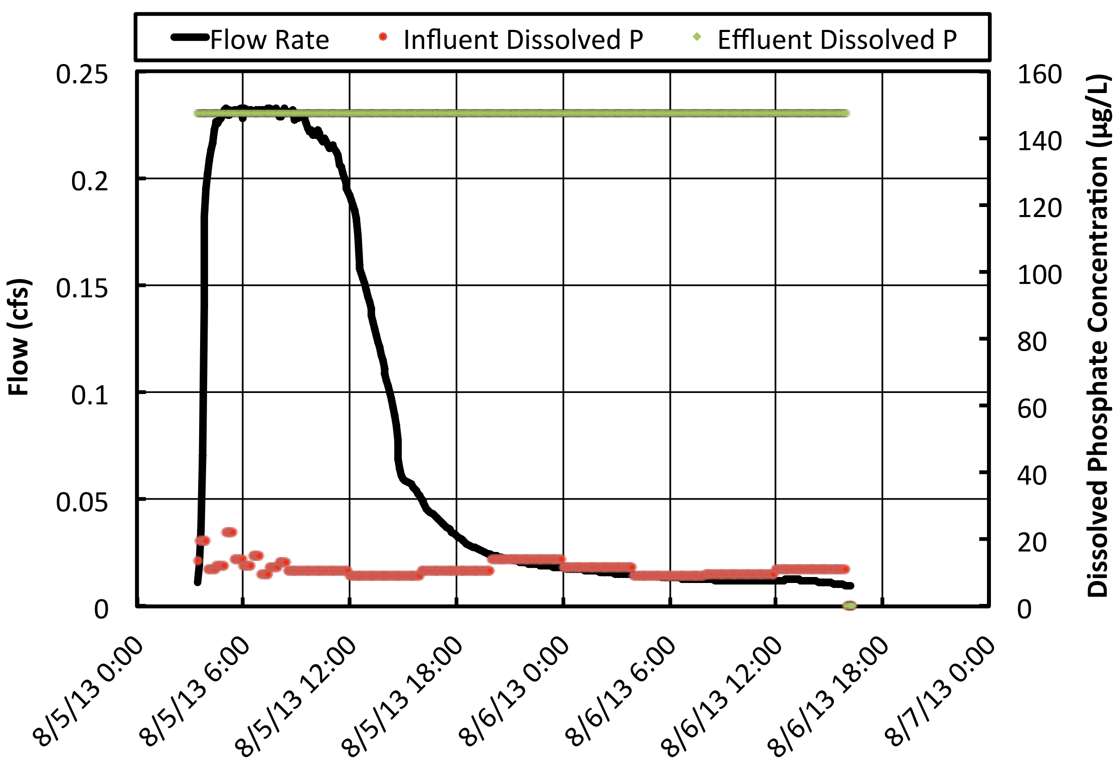

Figure B4. Flow and Pollutograph for event 2.

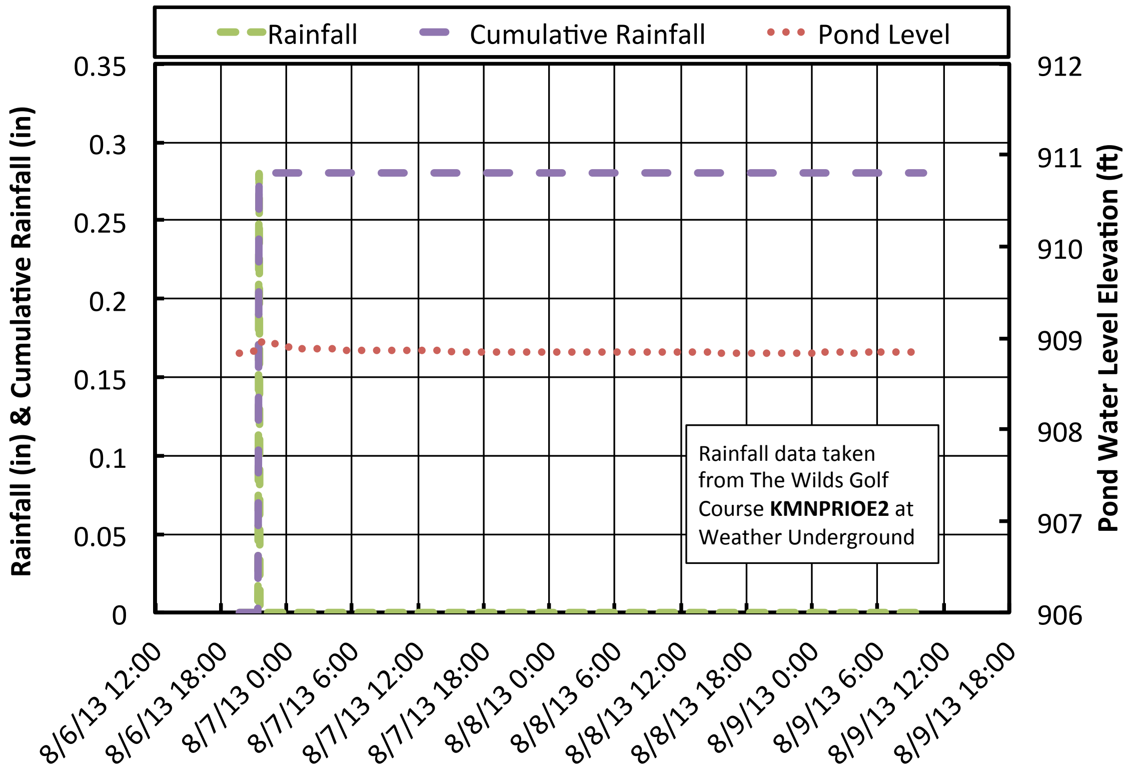

Figure B5. Rain and pond level for event 3.

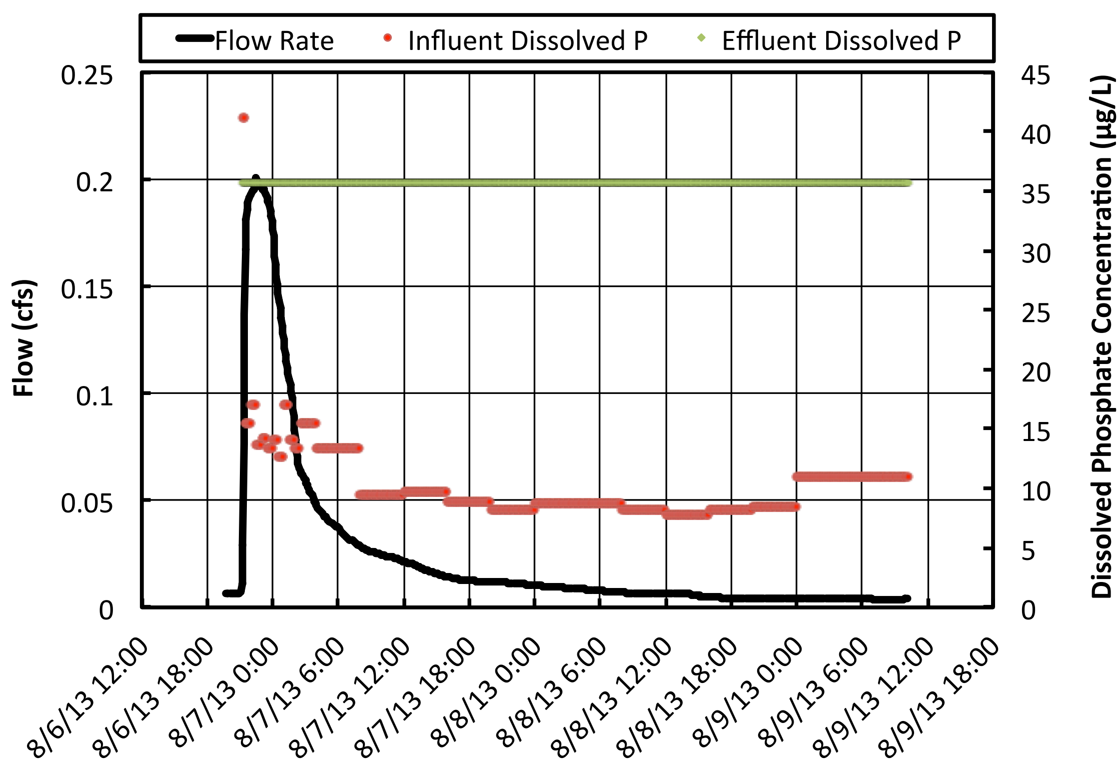

Figure B6. Flow and Pollutograph for event 3.

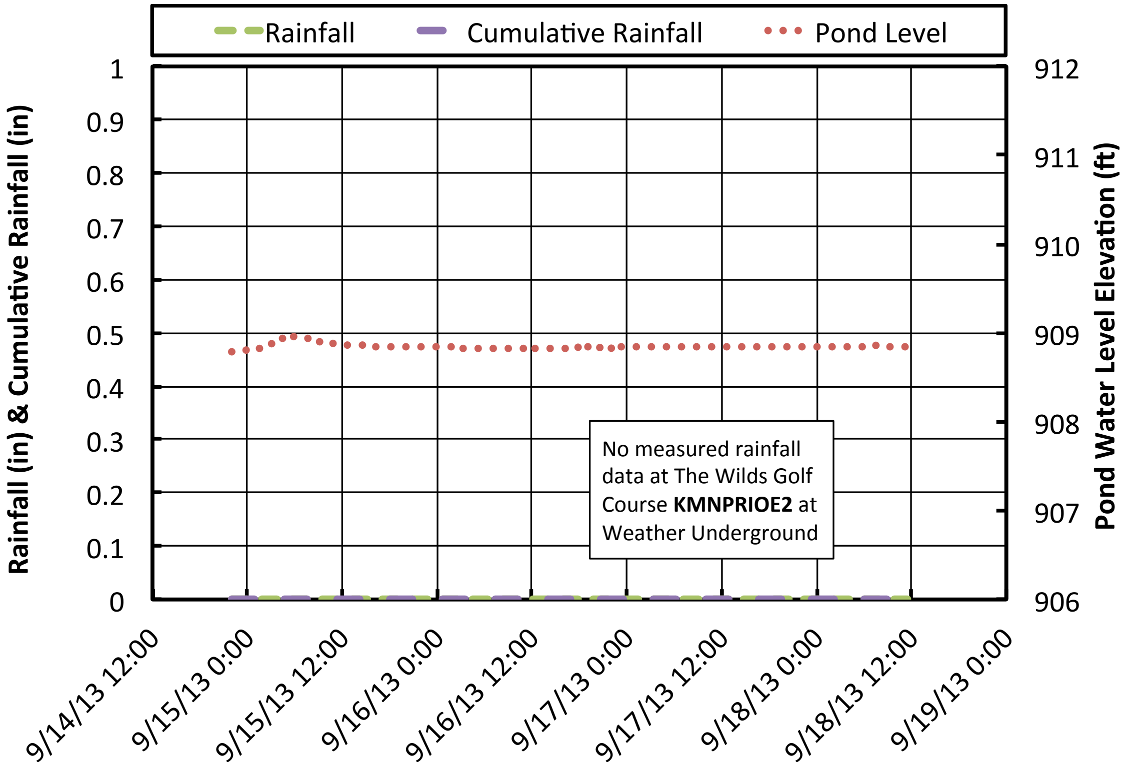

Figure B7. Rain and pond level for event 4.

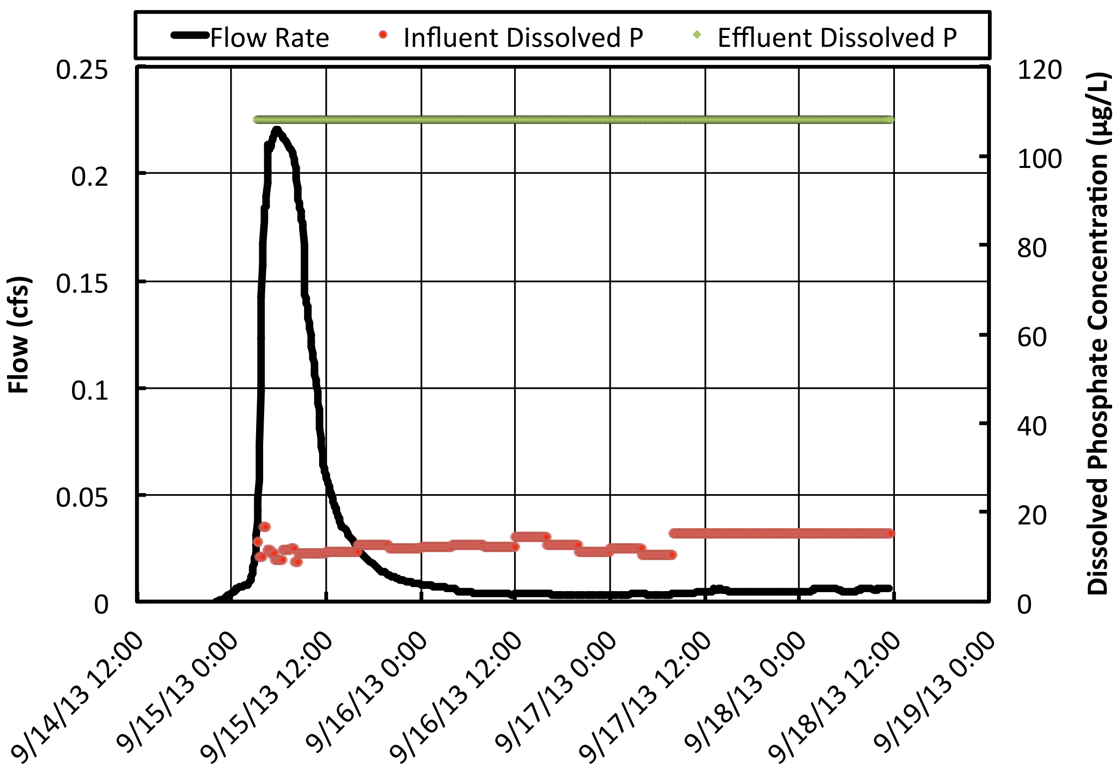

Figure B8. Flow and Pollutograph for event 4.

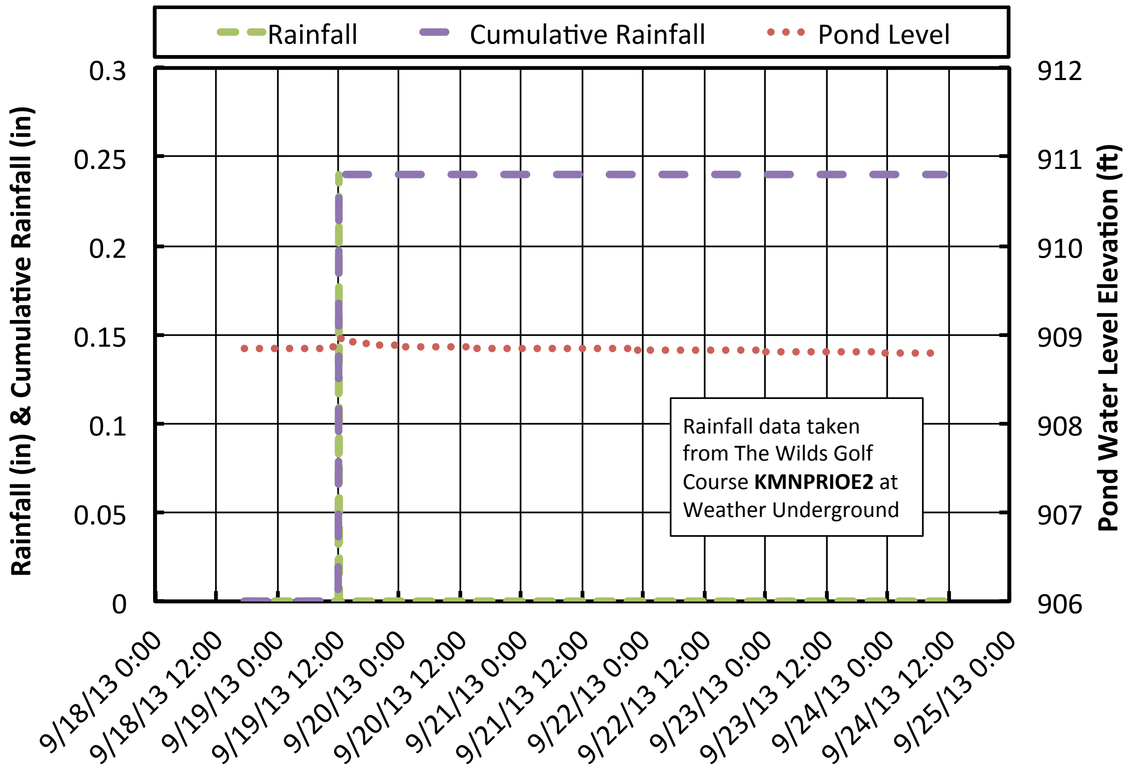

Figure B9. Rain and pond level for event 5.

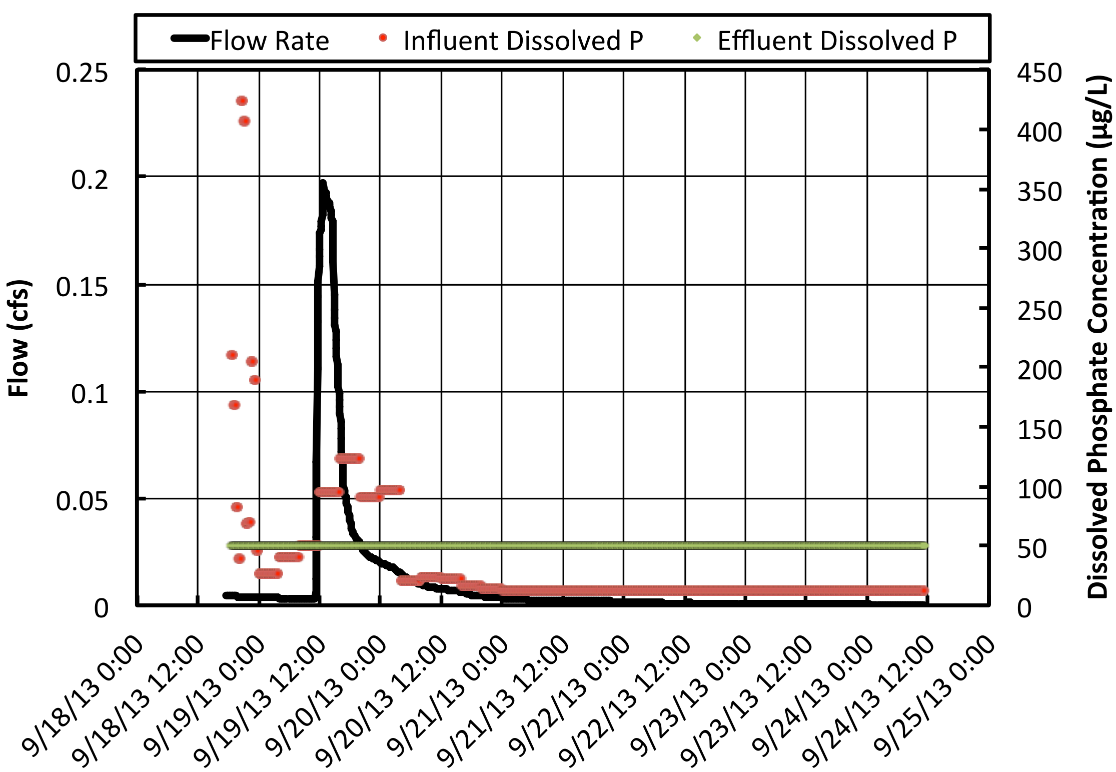

Figure B10. Flow and Pollutograph for event 5.

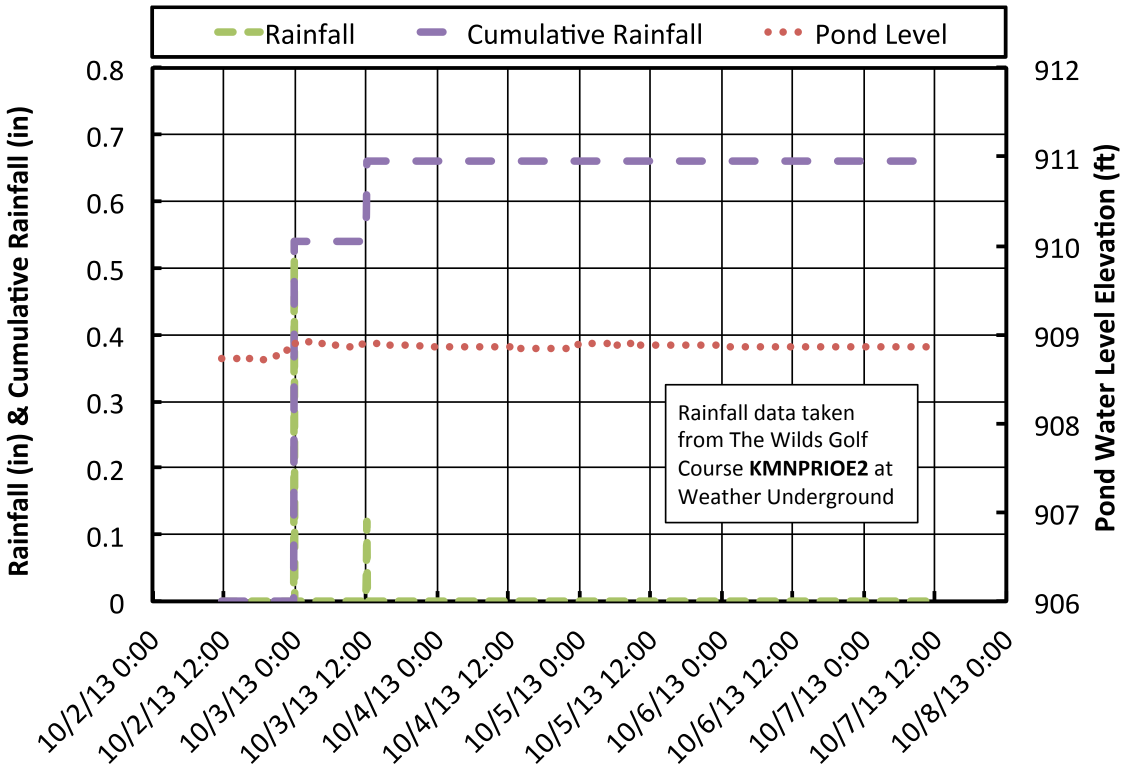

Figure B11. Rain and pond level for event 6.

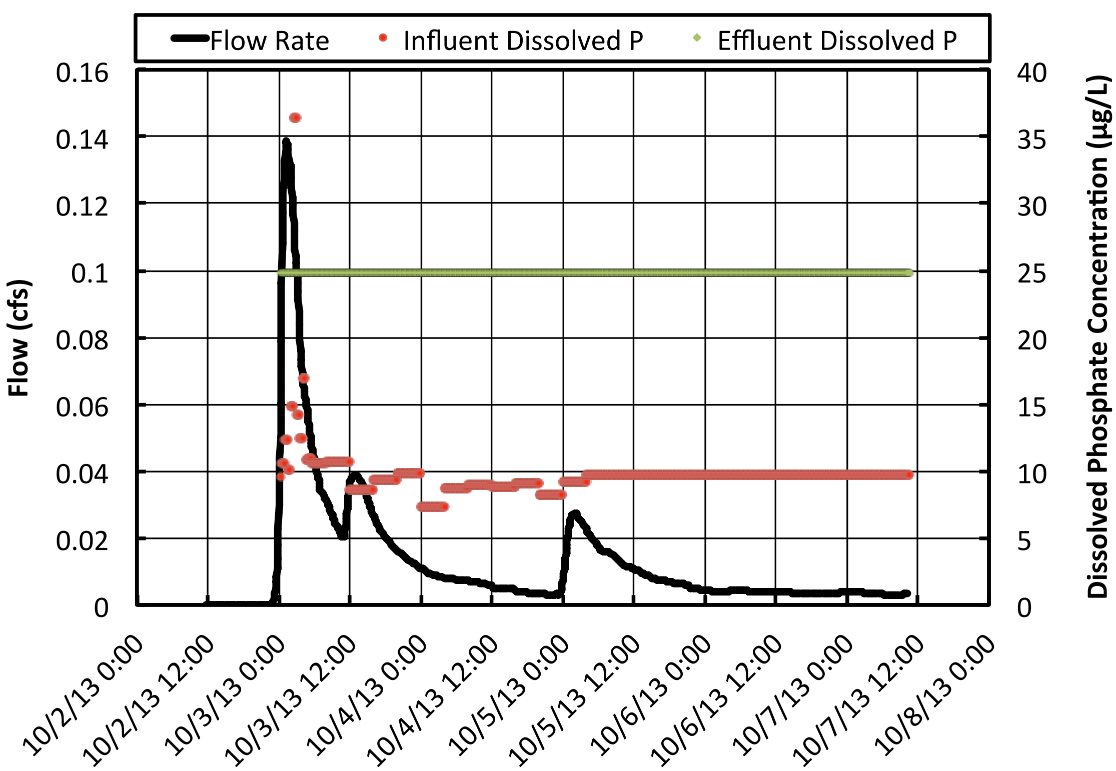

Figure B12. Flow and Pollutograph for event 6.

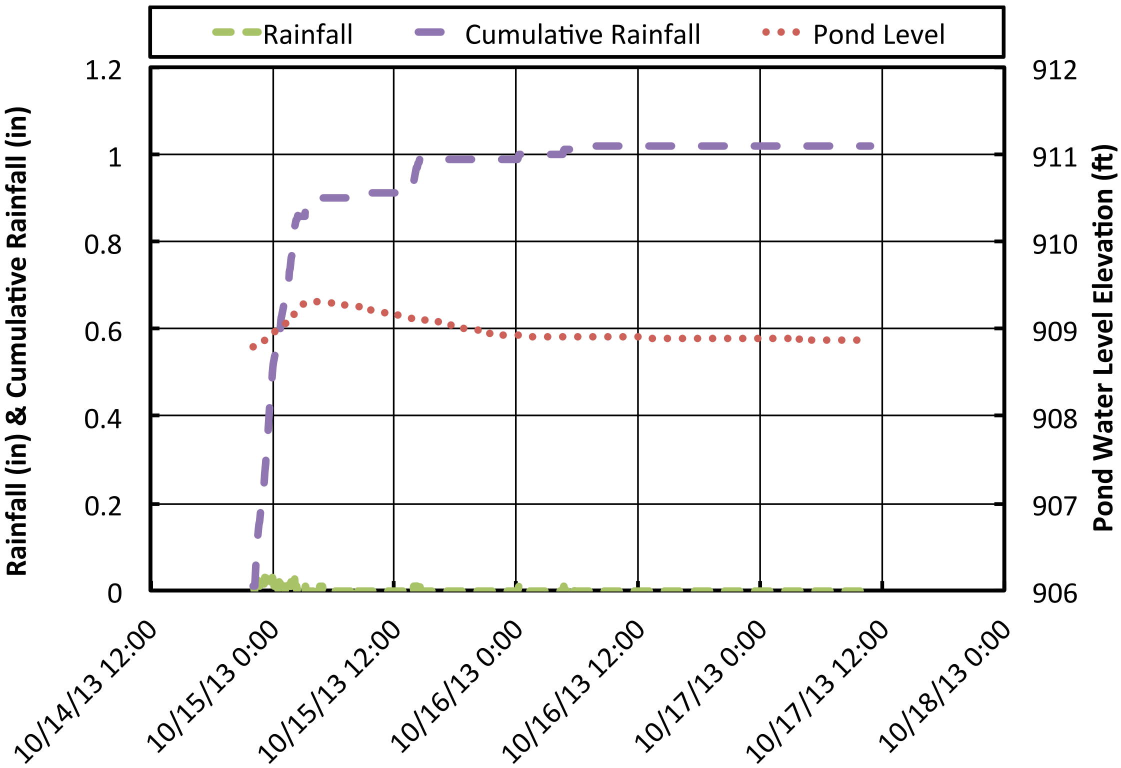

Figure B13. Rain and pond level for event 7.

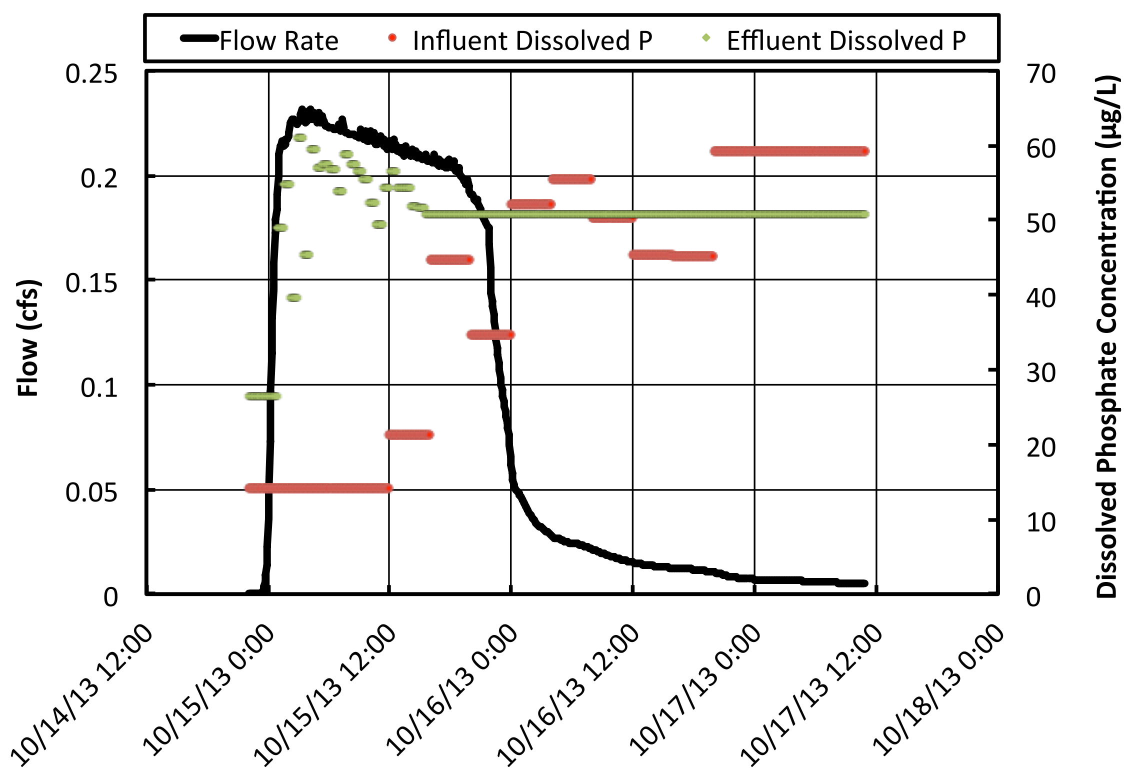

Figure B14. Flow and Pollutograph for event 7.

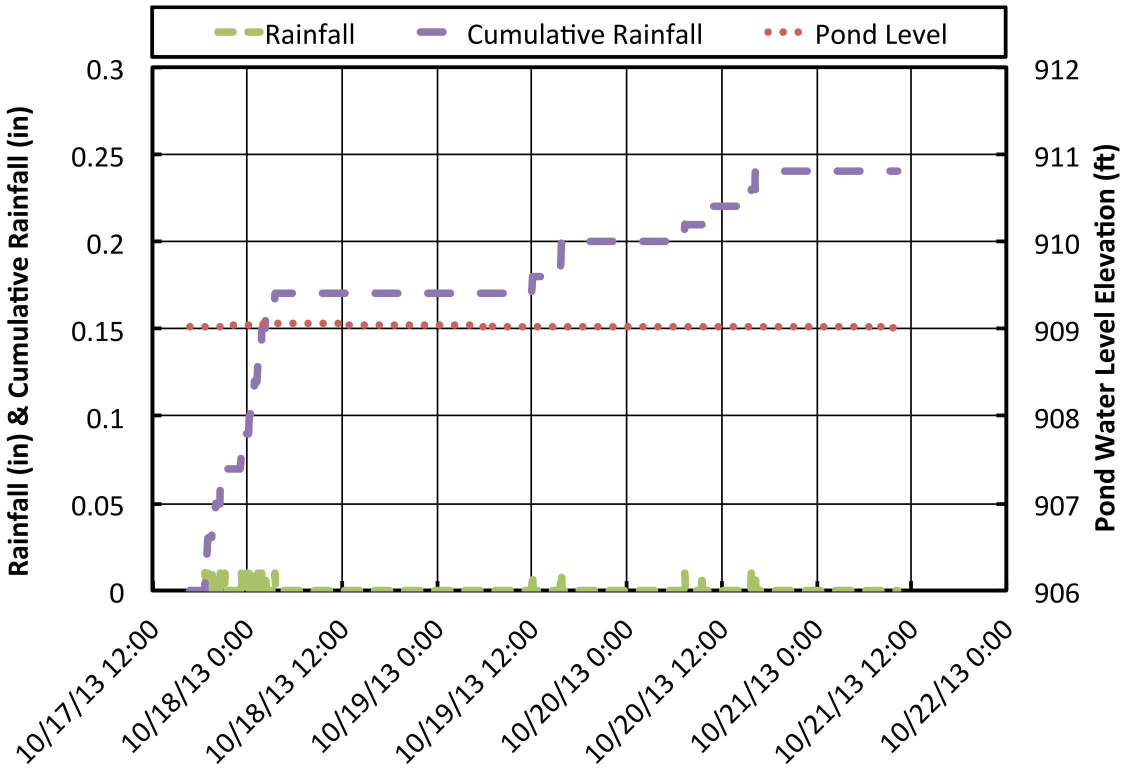

Figure B15. Rainand pond level for event 8.

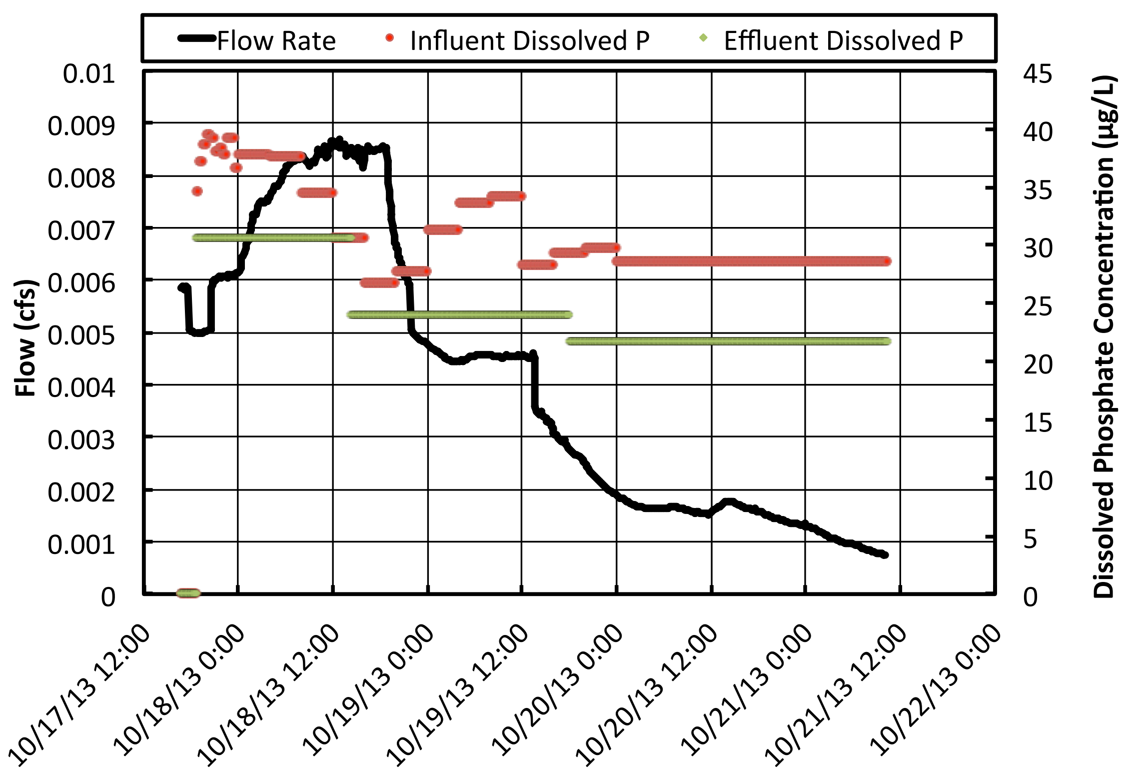

Figure B16. Flow and Pollutograph for event 8.

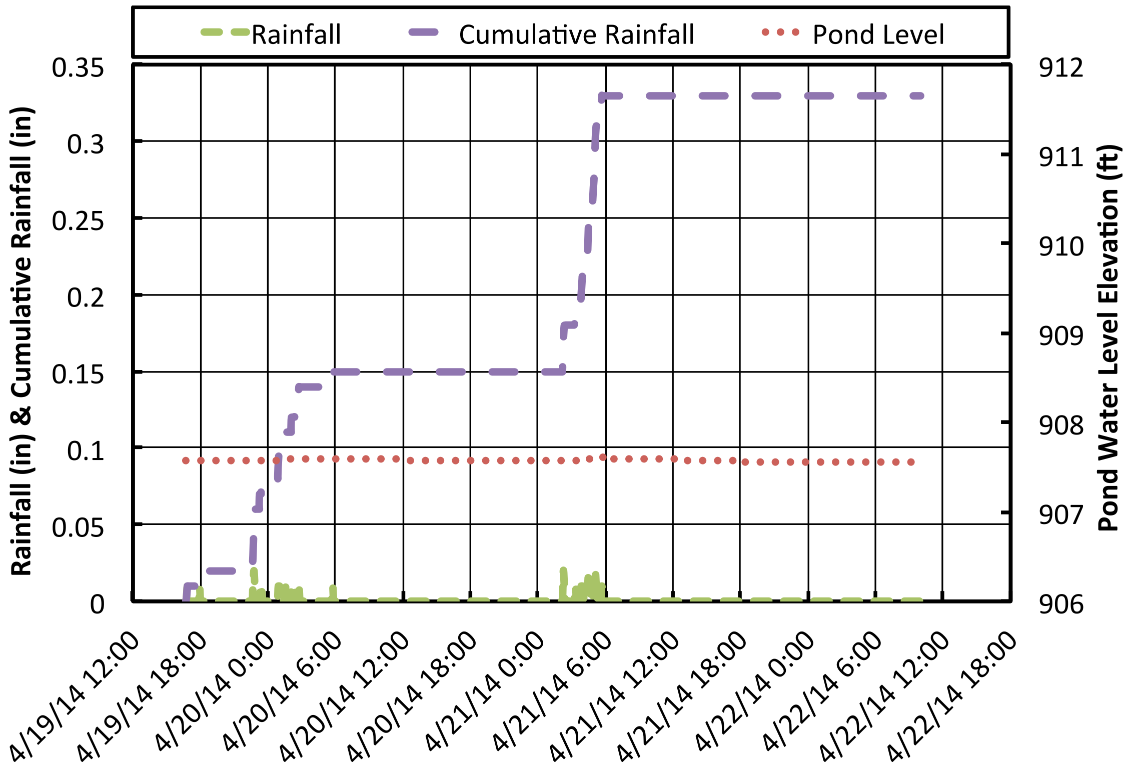

Figure B17. Rain and pond level for event 9.

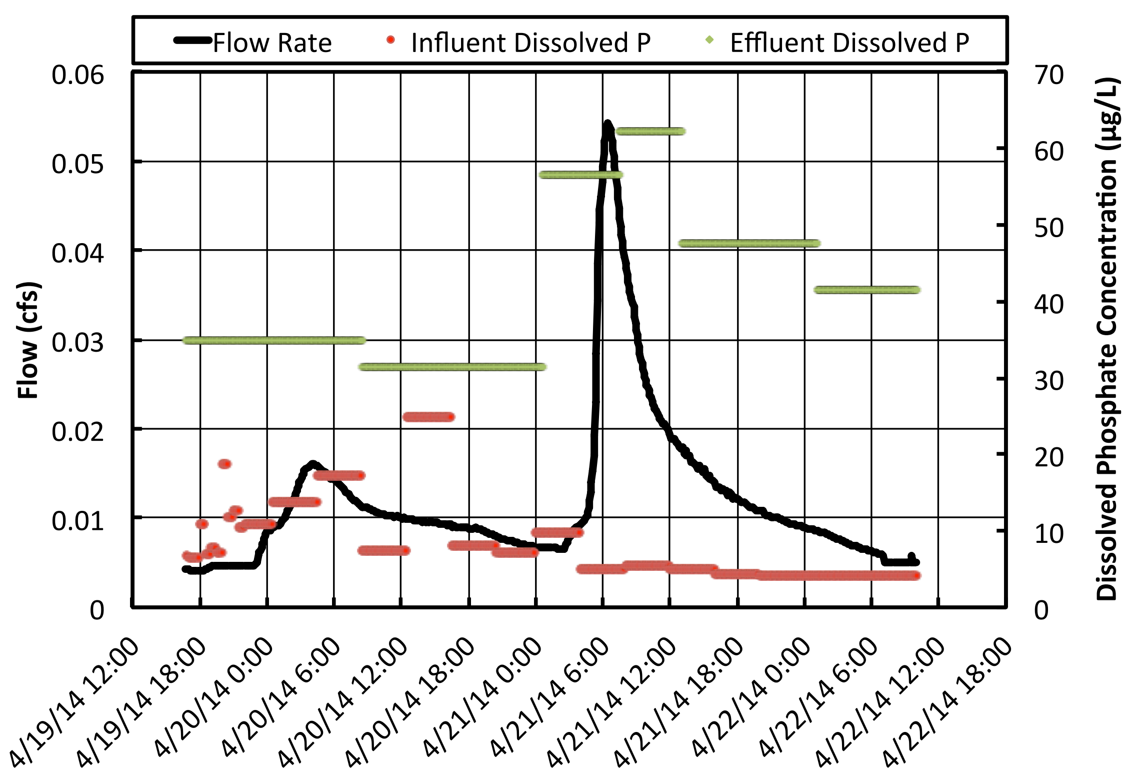

Figure B18. Flow and Pollutograph for event 9.

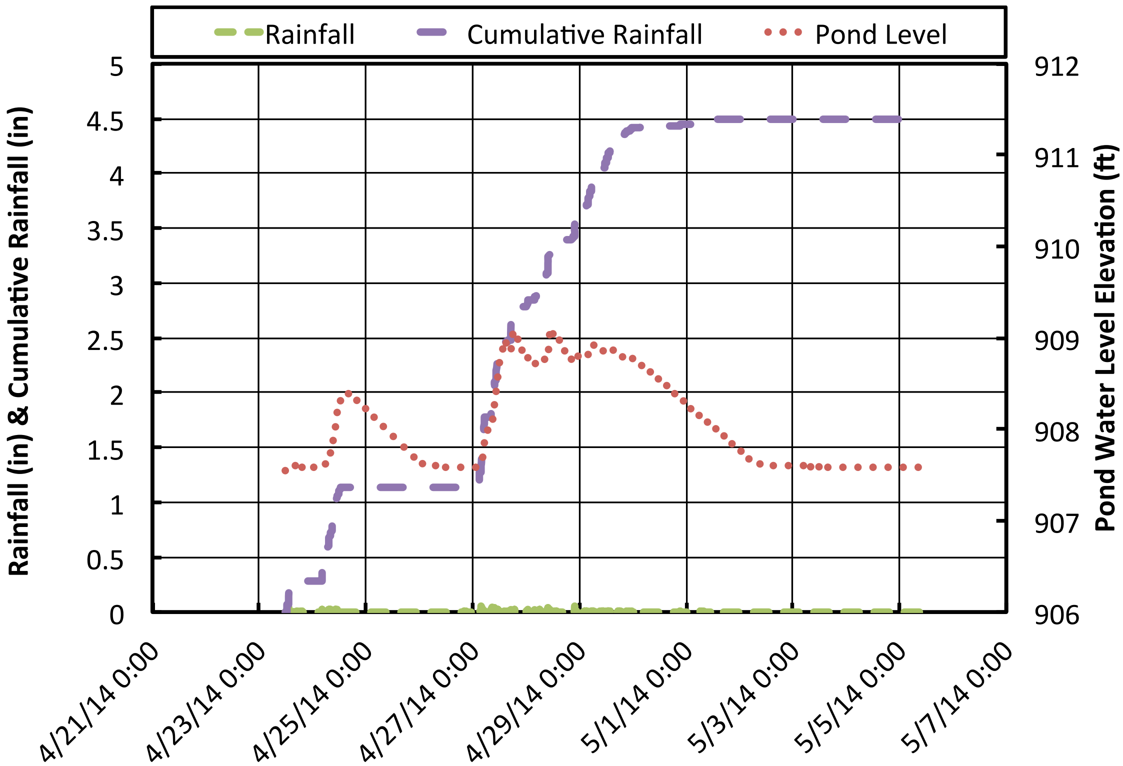

Figure B19. Rain and pond level for event 10.

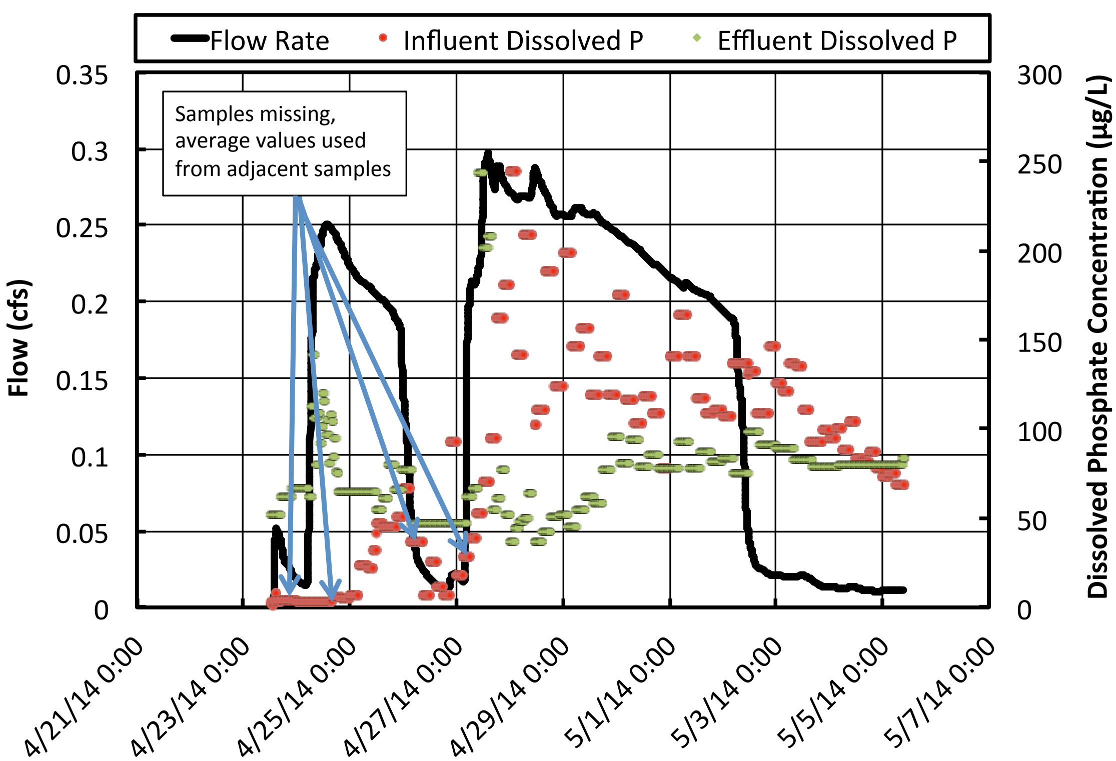

Figure B20. Flow and Pollutograph for event 10.

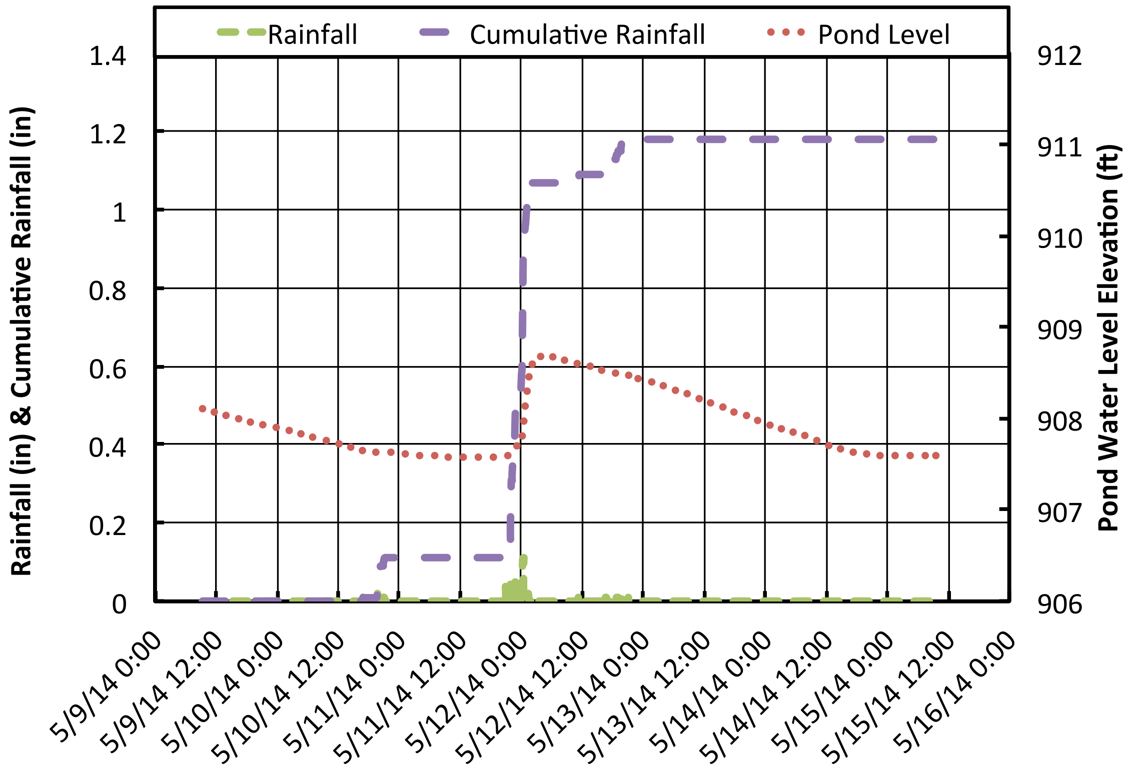

Figure B21. Rain and pond level for event 11.

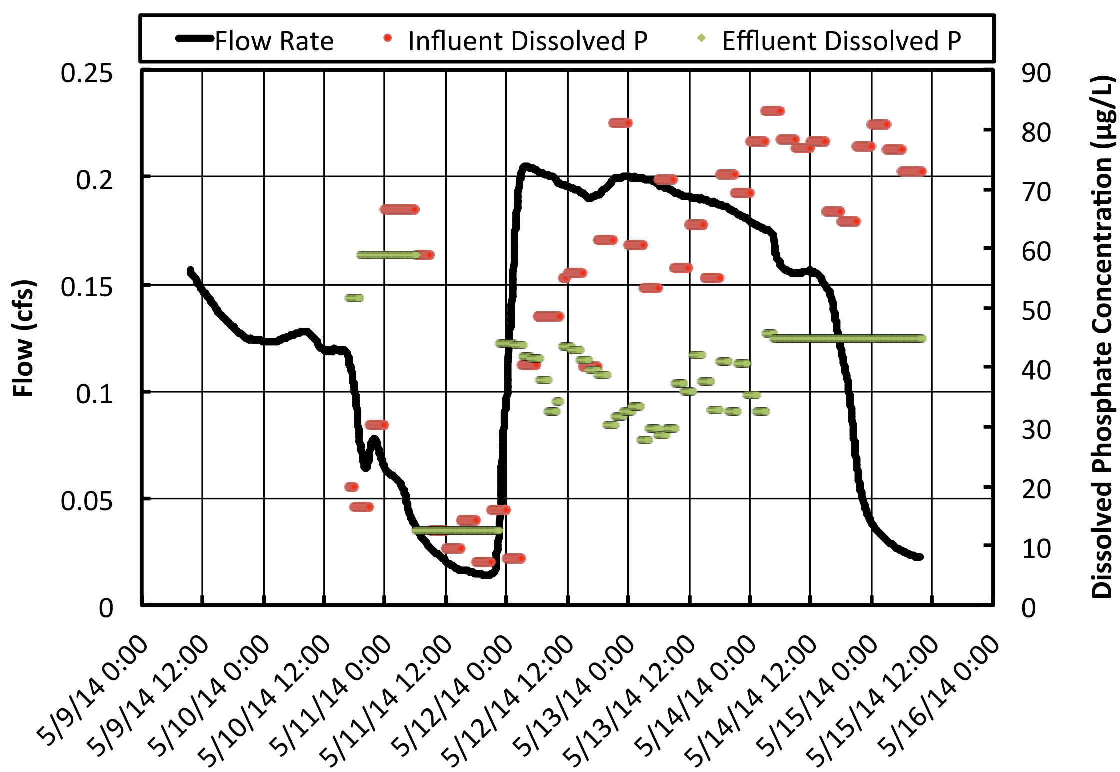

Figure B22. Flow and Pollutograph for event 11.

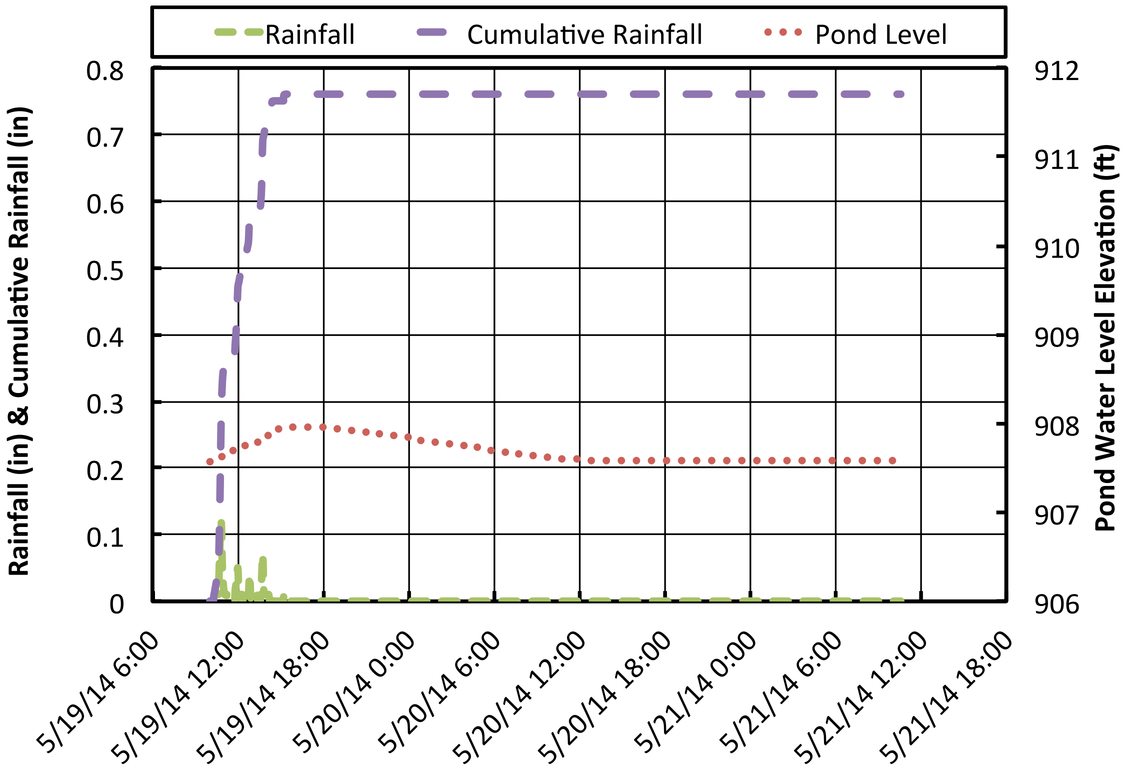

Figure B23. Rain and pond level for event 12.

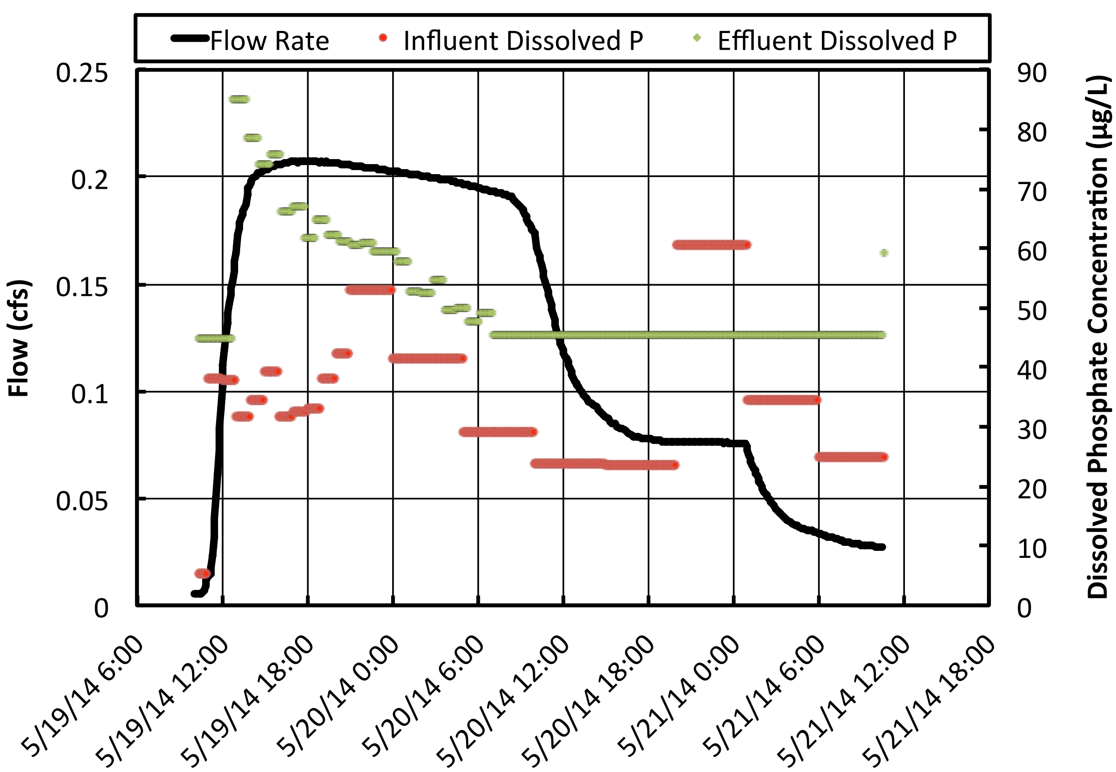

Figure B24. Flow and Pollutograph for event 12.

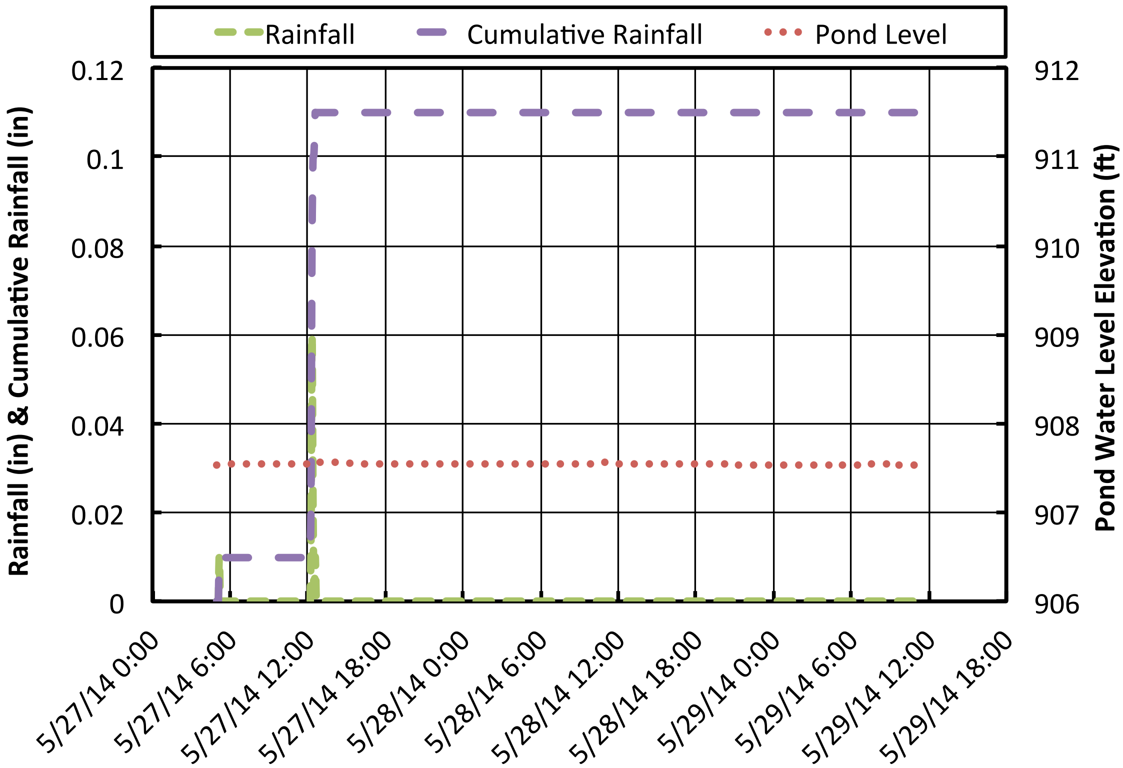

Figure B25. Rain and pond level for event 13.

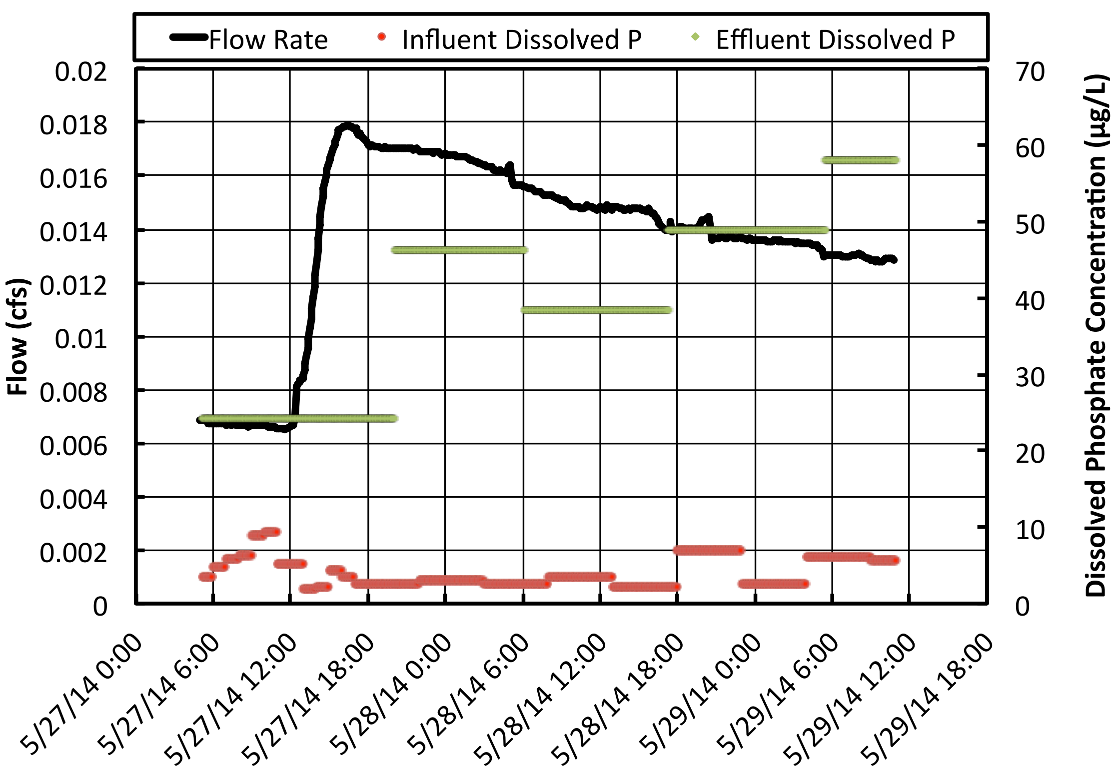

Figure B26. Flow and Pollutograph for event 13.

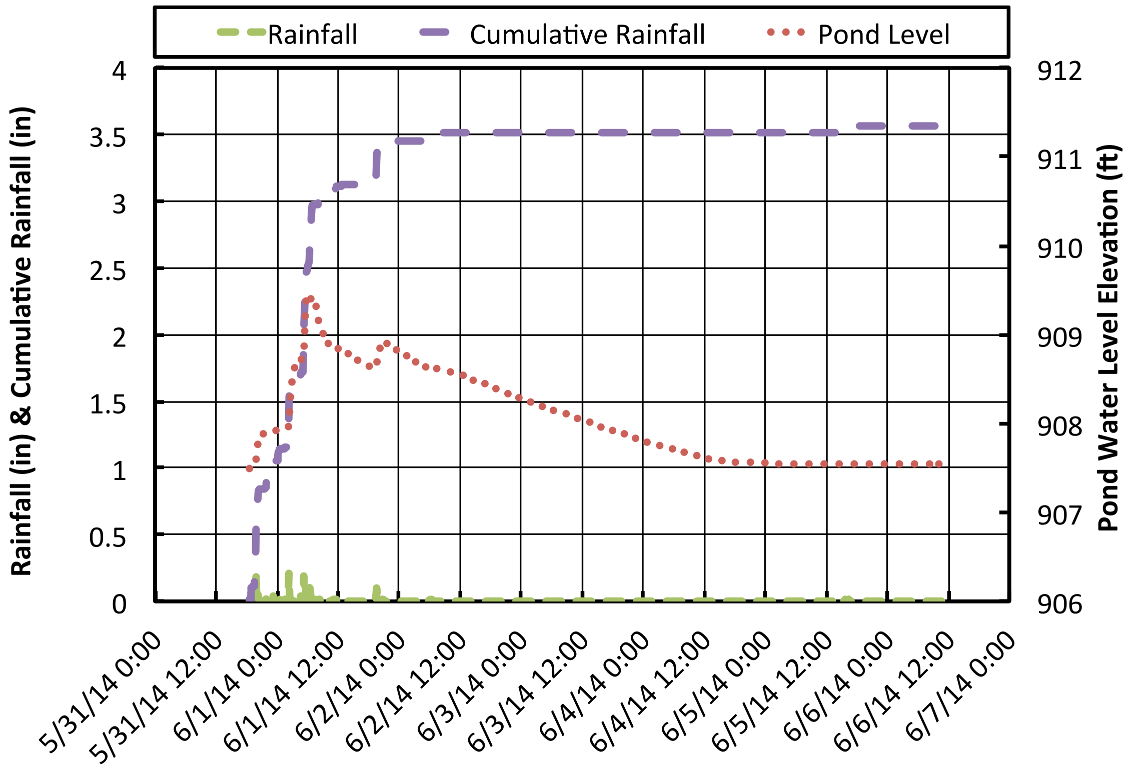

Figure B27. Rain and pond level for event 14.

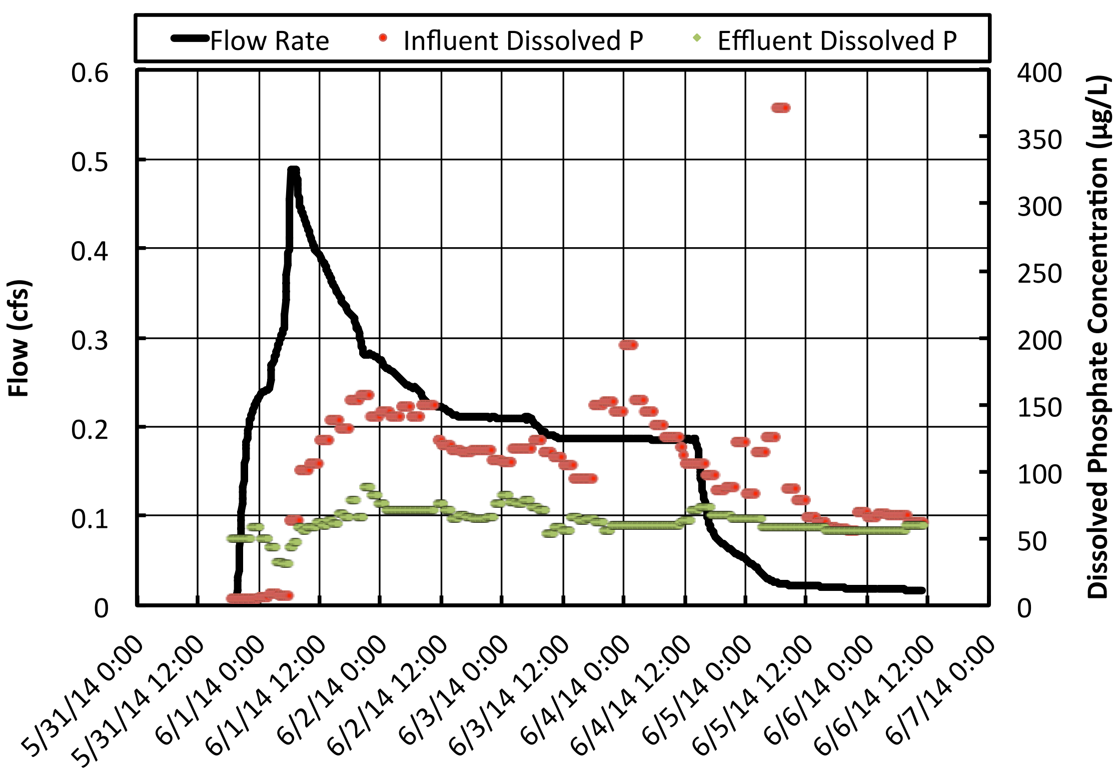

Figure B28. Flow and Pollutograph for even 14.

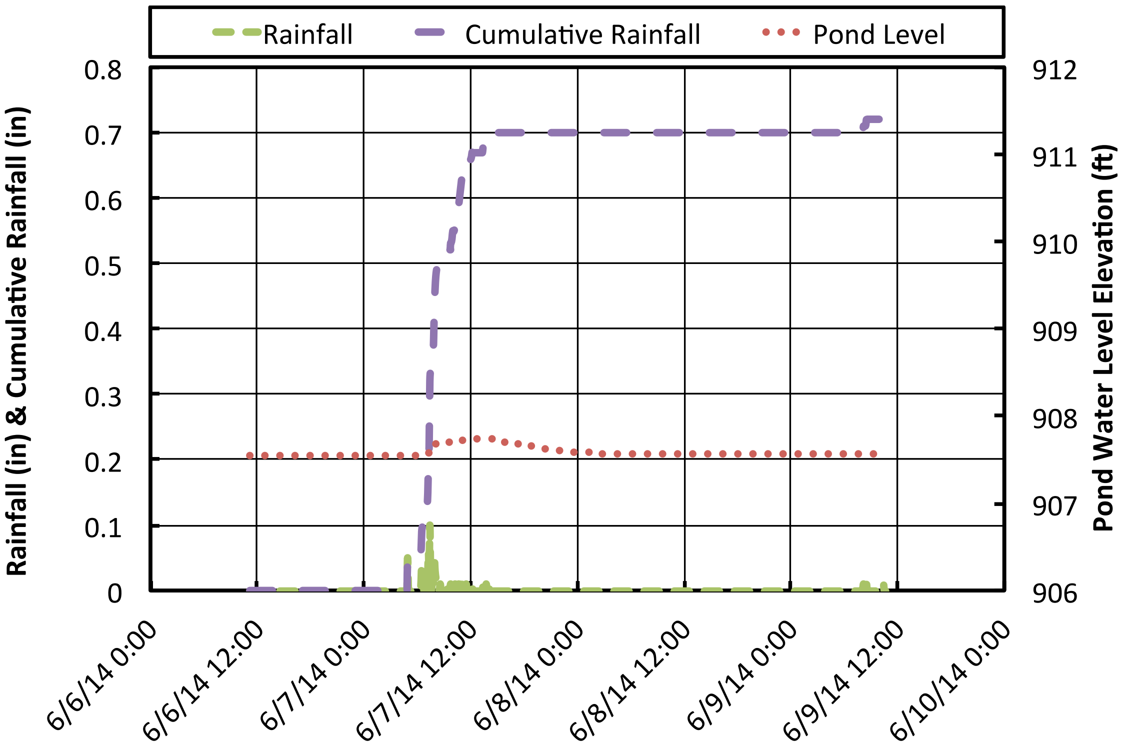

Figure B29. Rain and pond level for event 15.

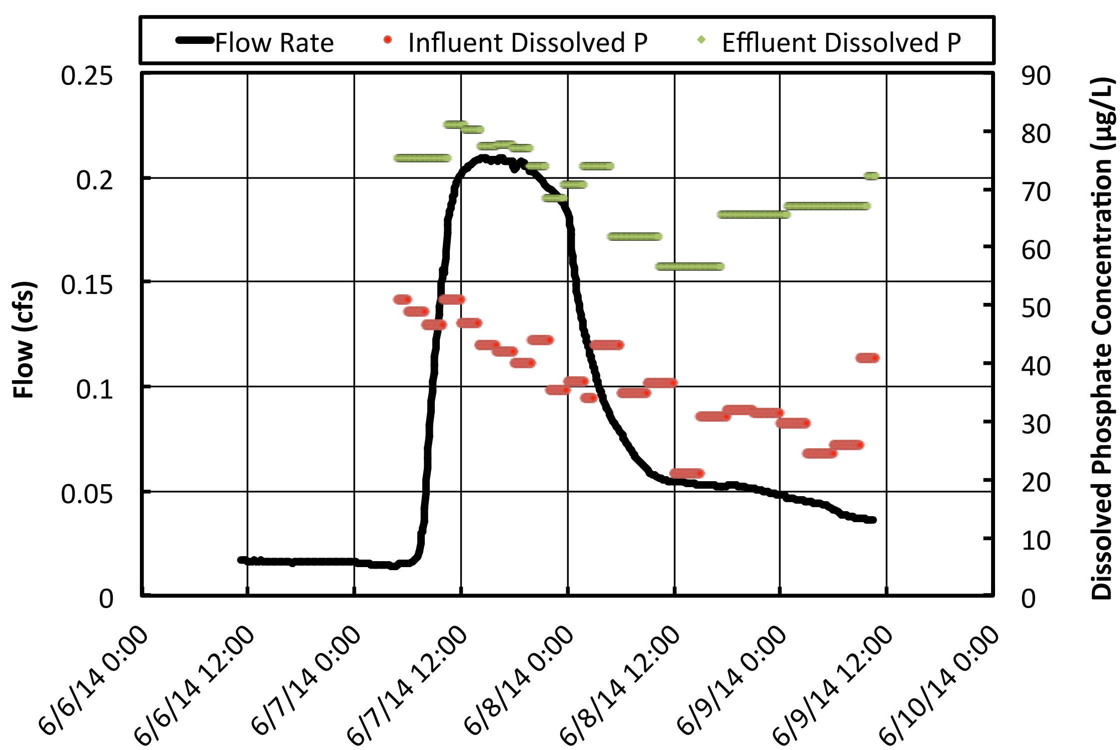

Figure B30. Flow and Pollutograph for event 15.

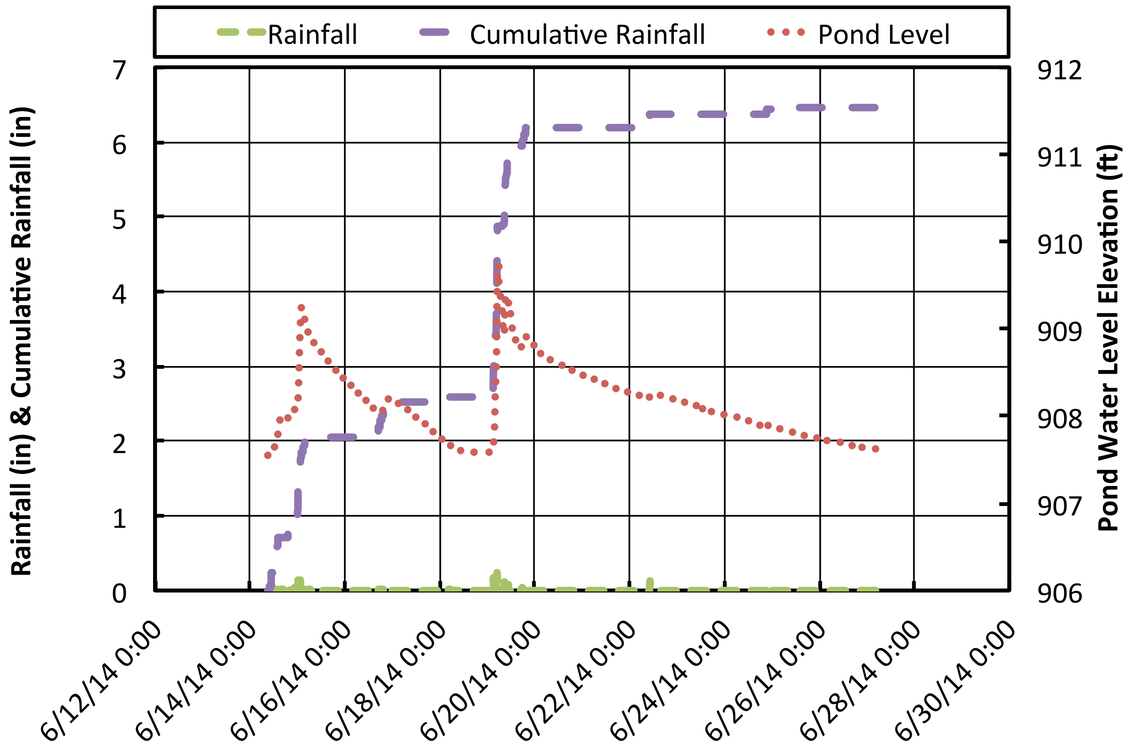

Figure B31. Rain and pond level for event 16.

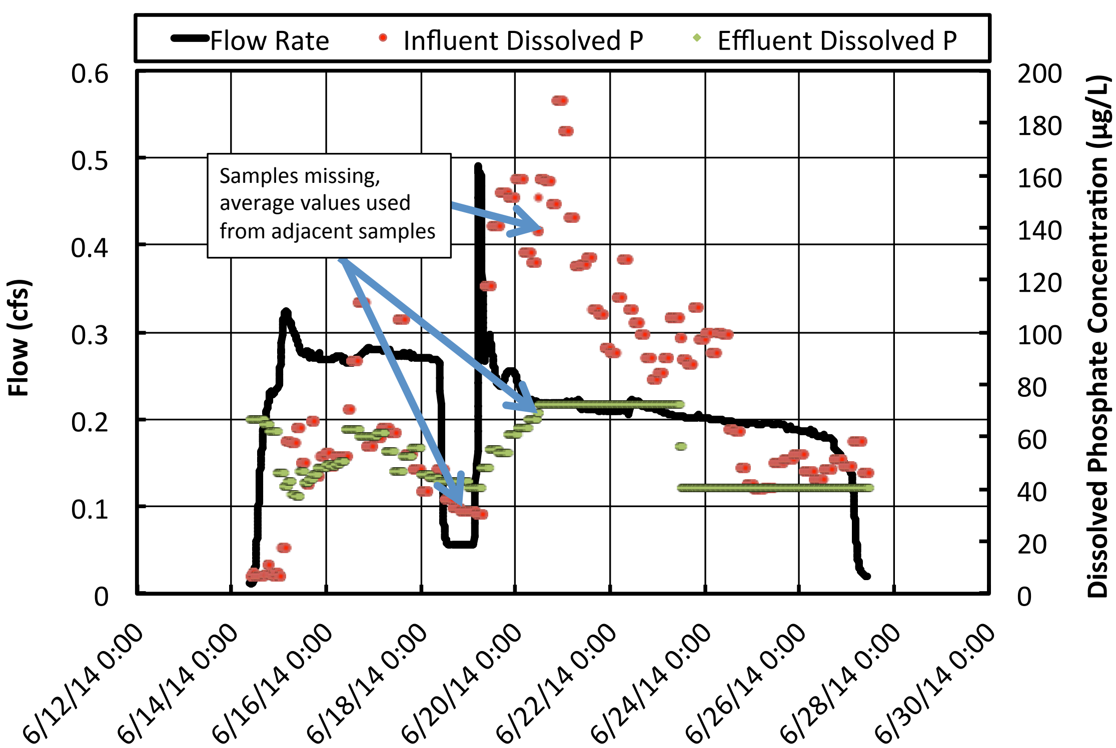

Figure B32. Flow and Pollutograph for event 16.

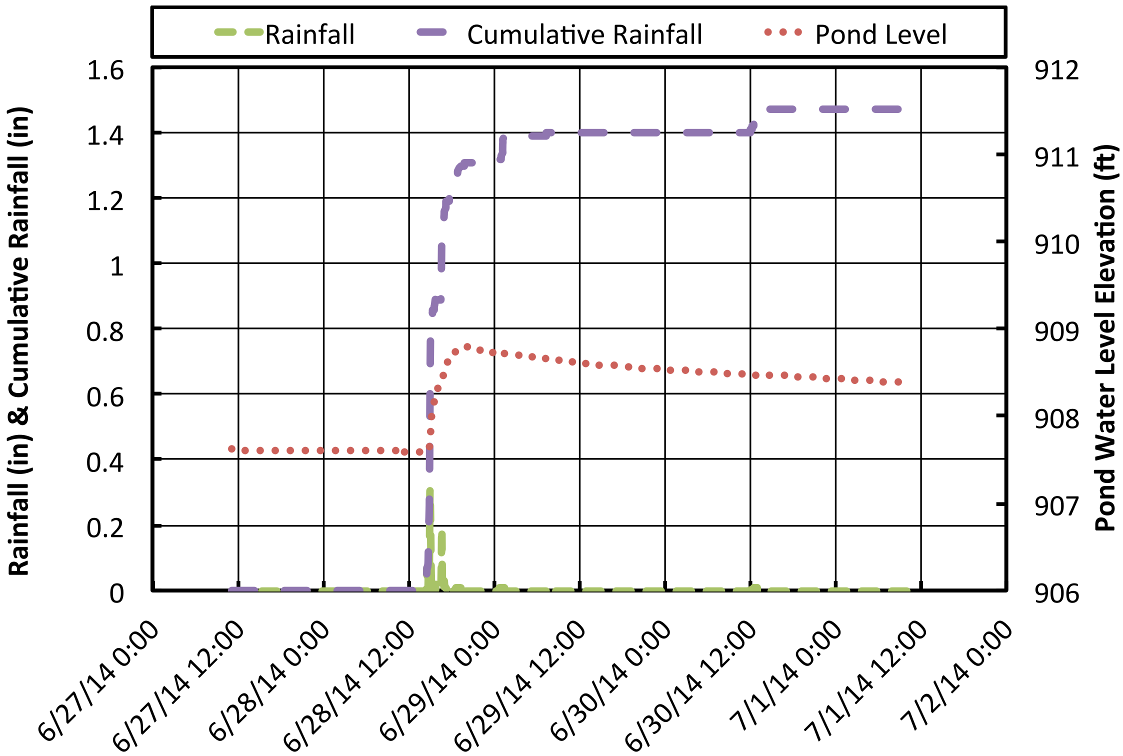

Figure B33. Rain and pond level for event 17.

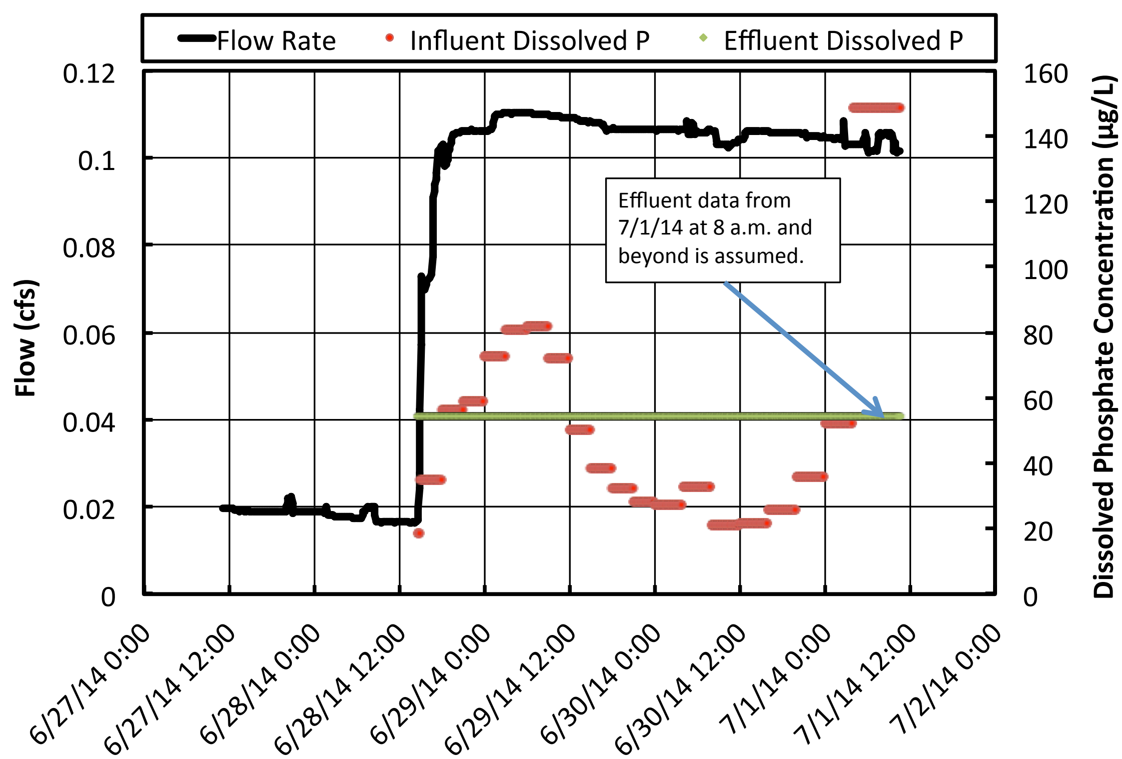

Figure B34. Flow and Pollutograph for event 17.

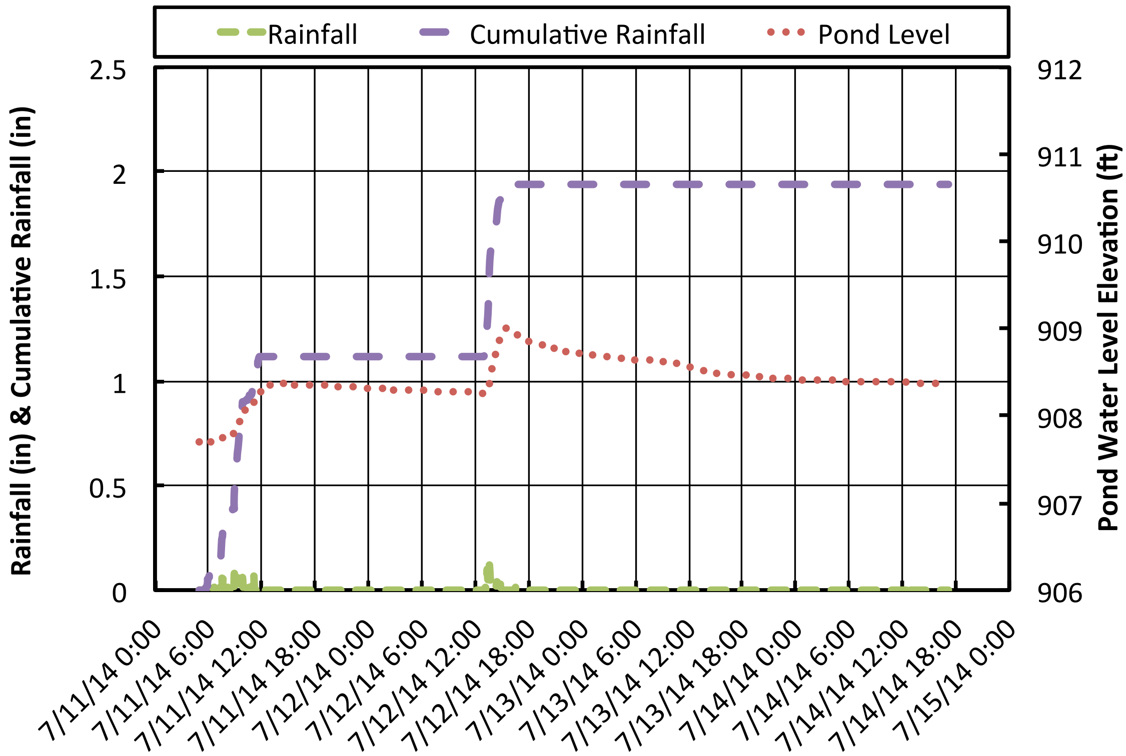

Figure B35. Rain and pond level for event 18.

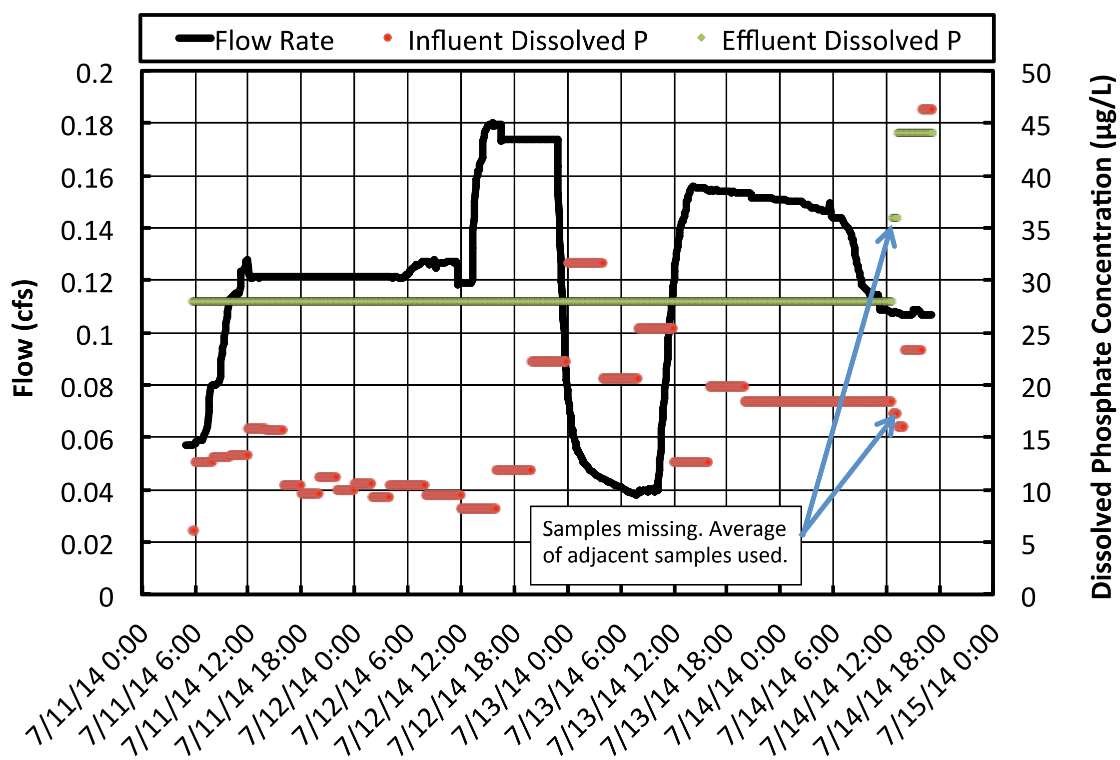

Figure B36. Flow and Pollutograph fro event 18.

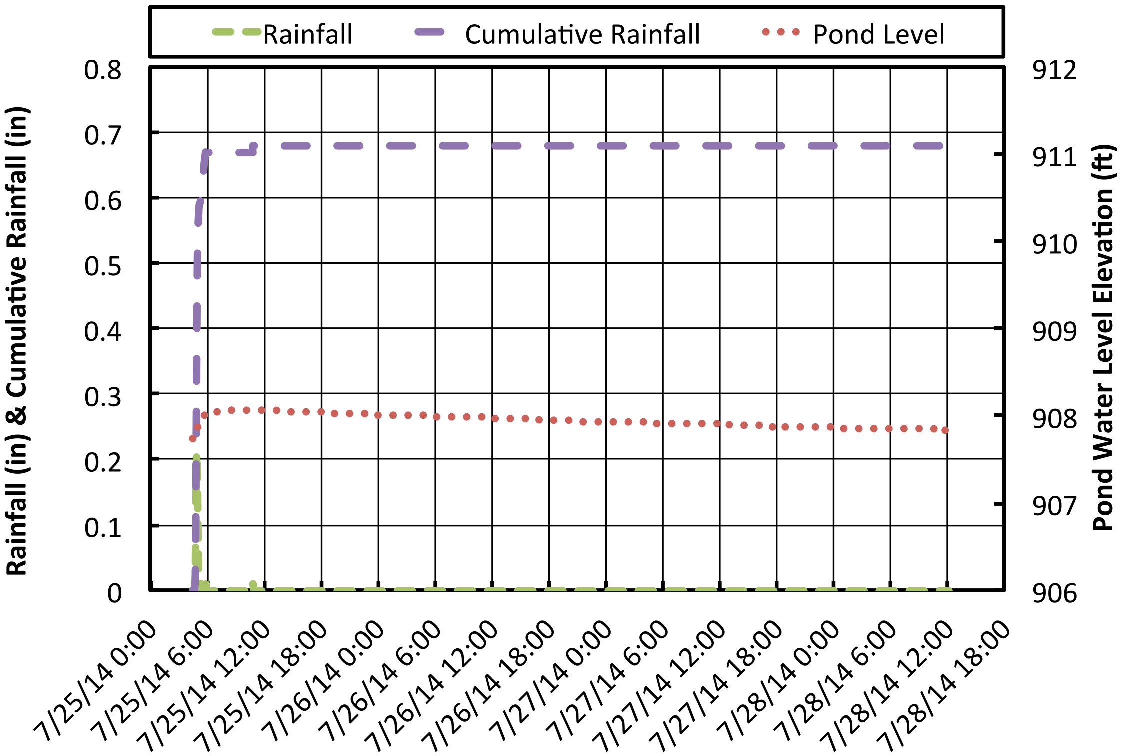

Figure B37. Rain and pond level for event 19.

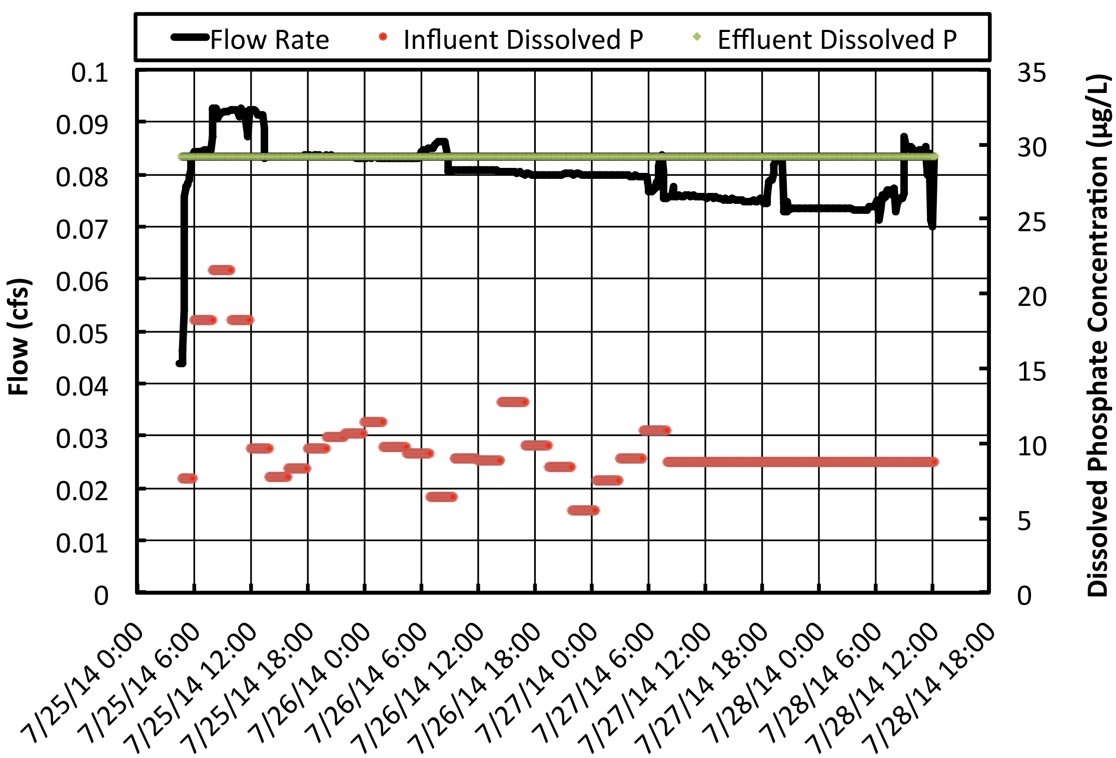

Figure B38. Flow and Pollutograph for event 19.

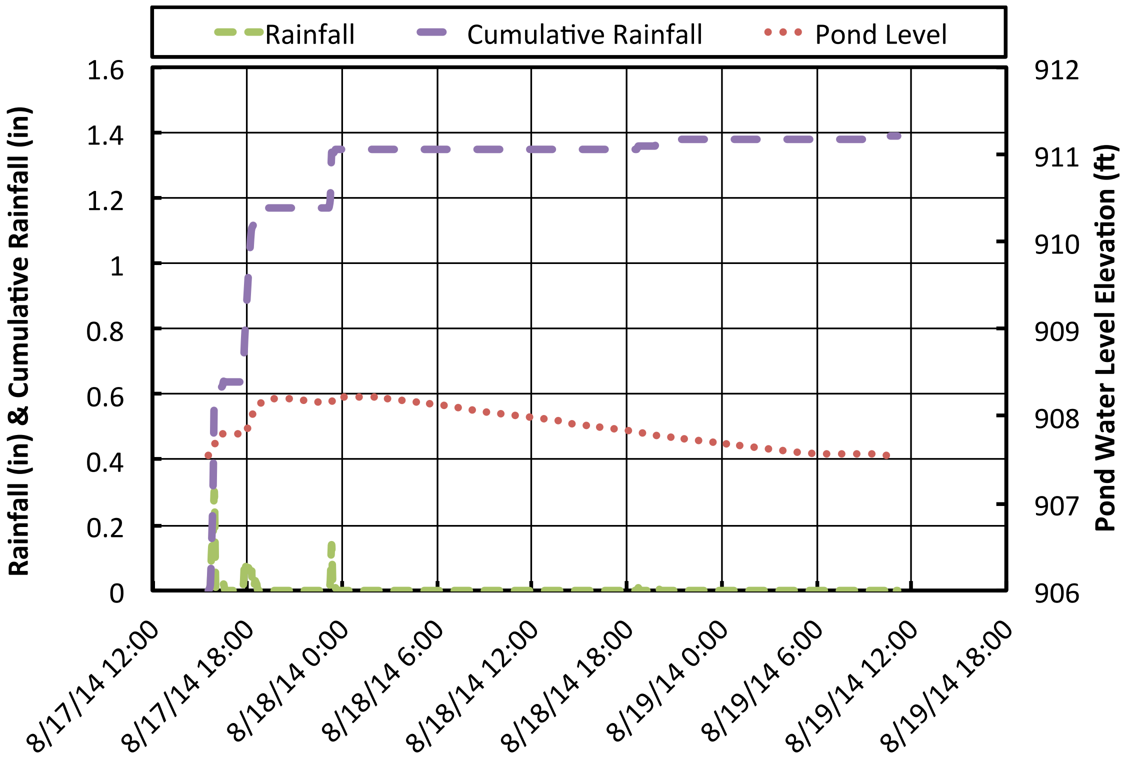

Figure B39. Rain and pond level for event 20.

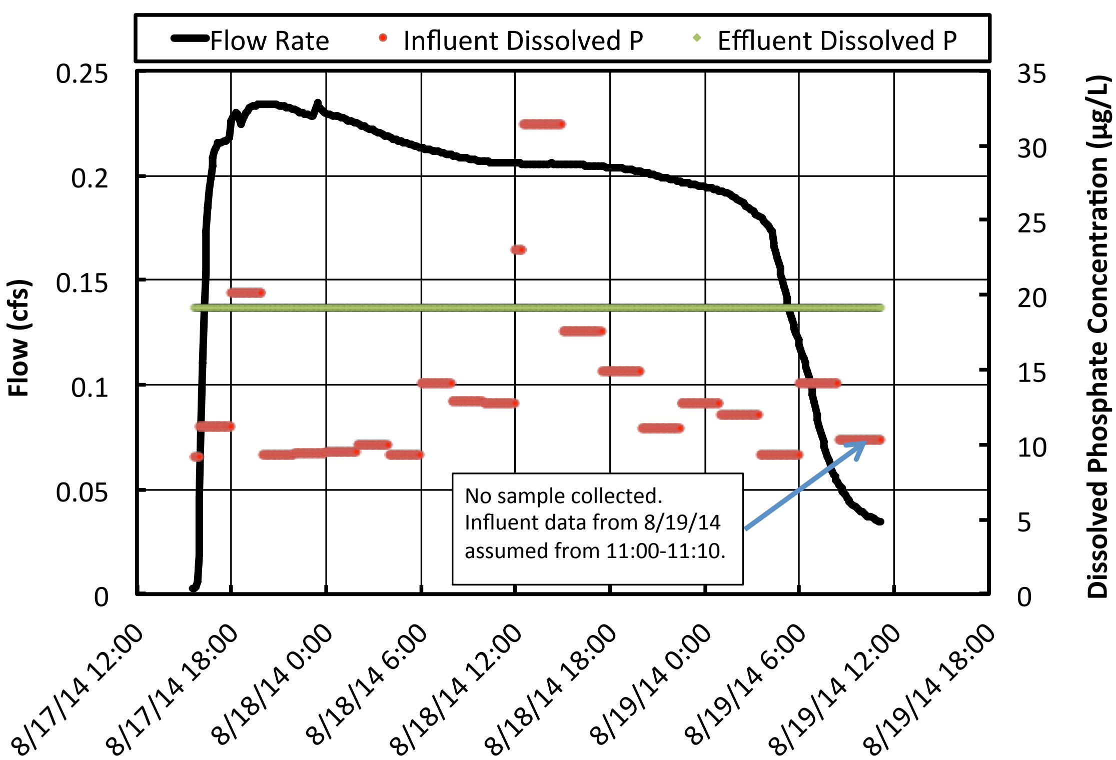

Figure B40. Flow and Pollutograph for event 20.

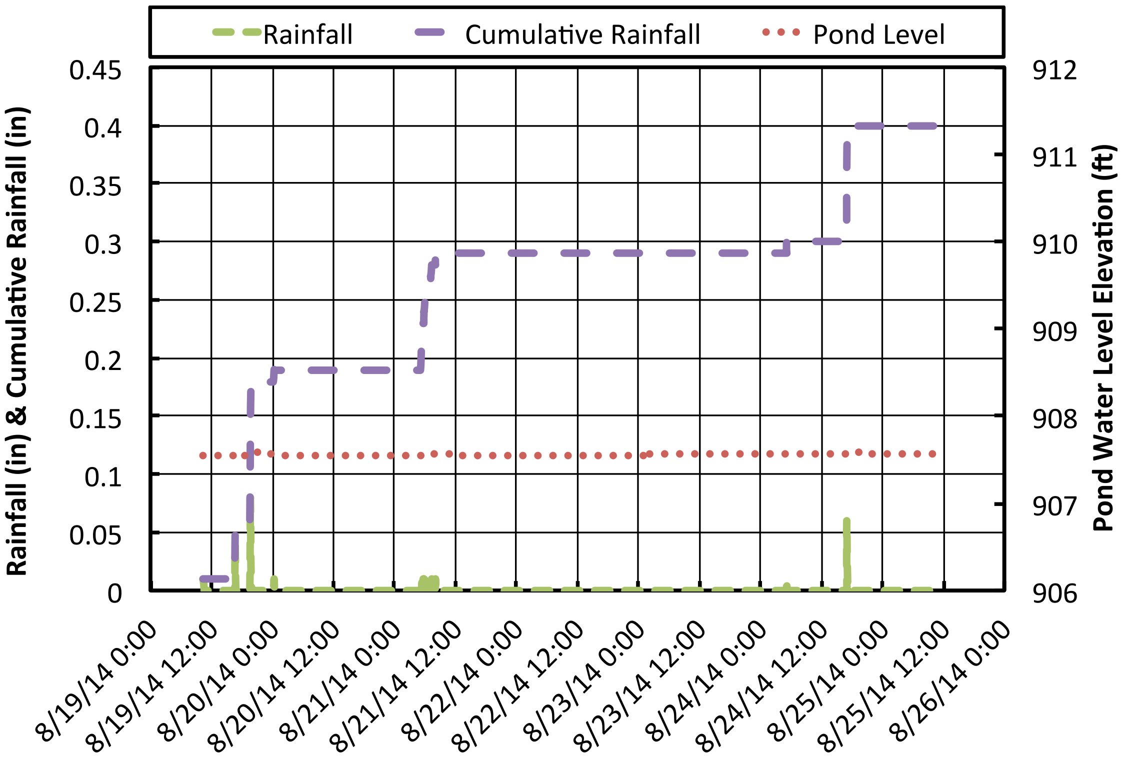

Figure B41. Rain and pond level for event 21.

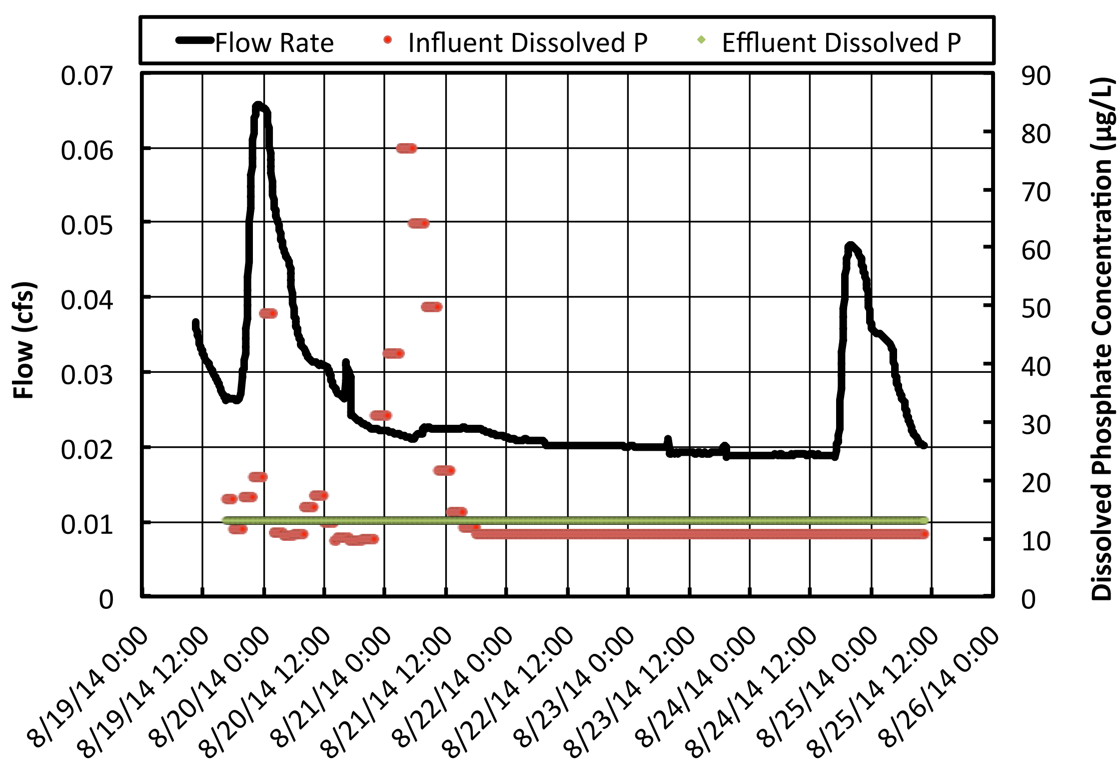

Figure B42. Flow and Pollutograph for event 21.

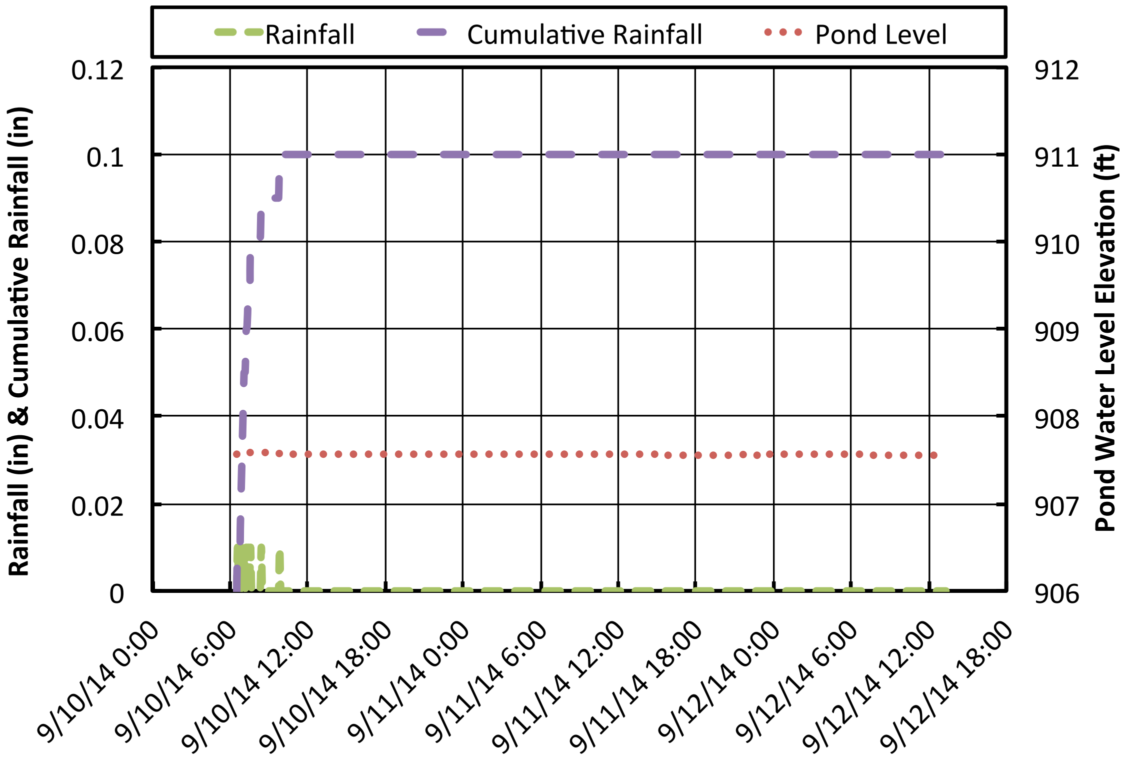

Figure B43. Rain and pond level for event 22.

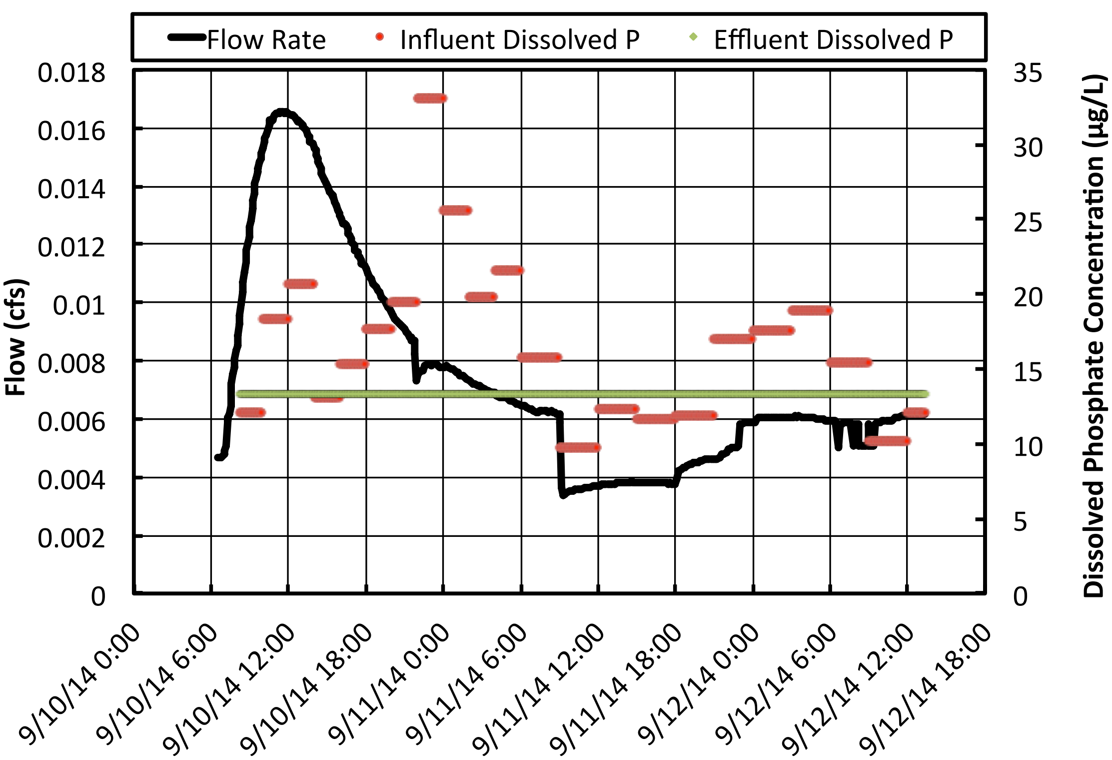

Figure B44. Flow and Pollutograph for event 22.

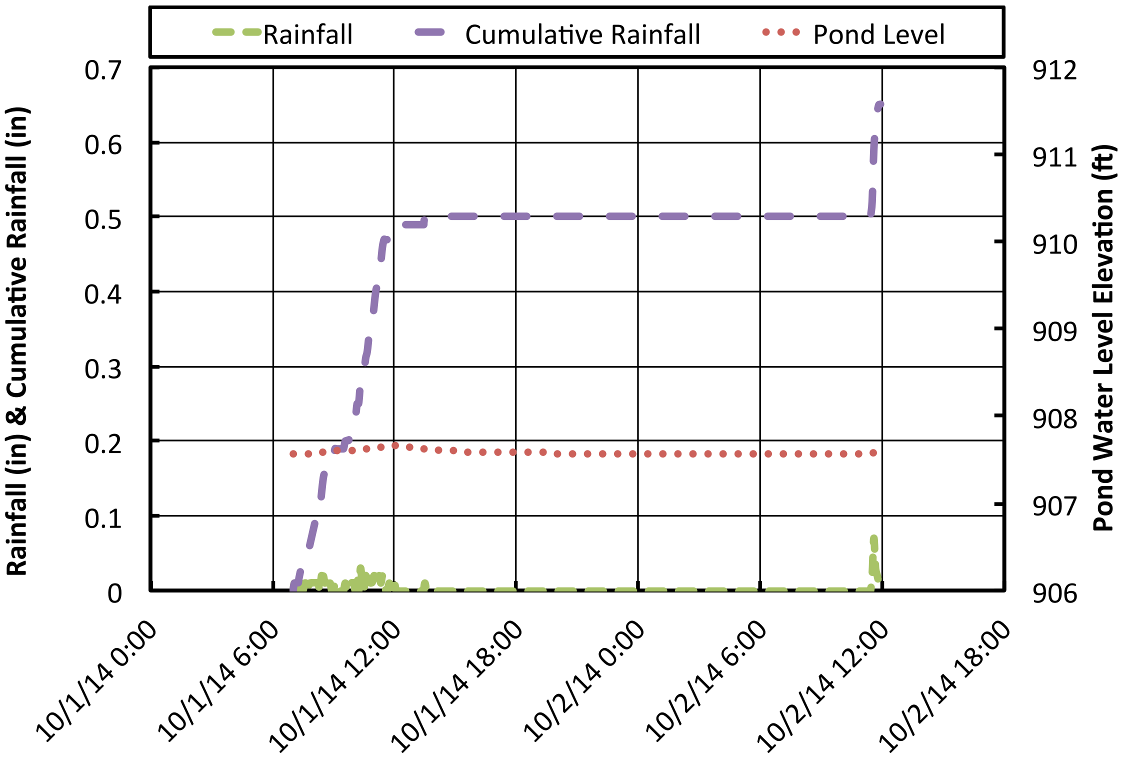

Figure B45. Rain and pond level for event 23.

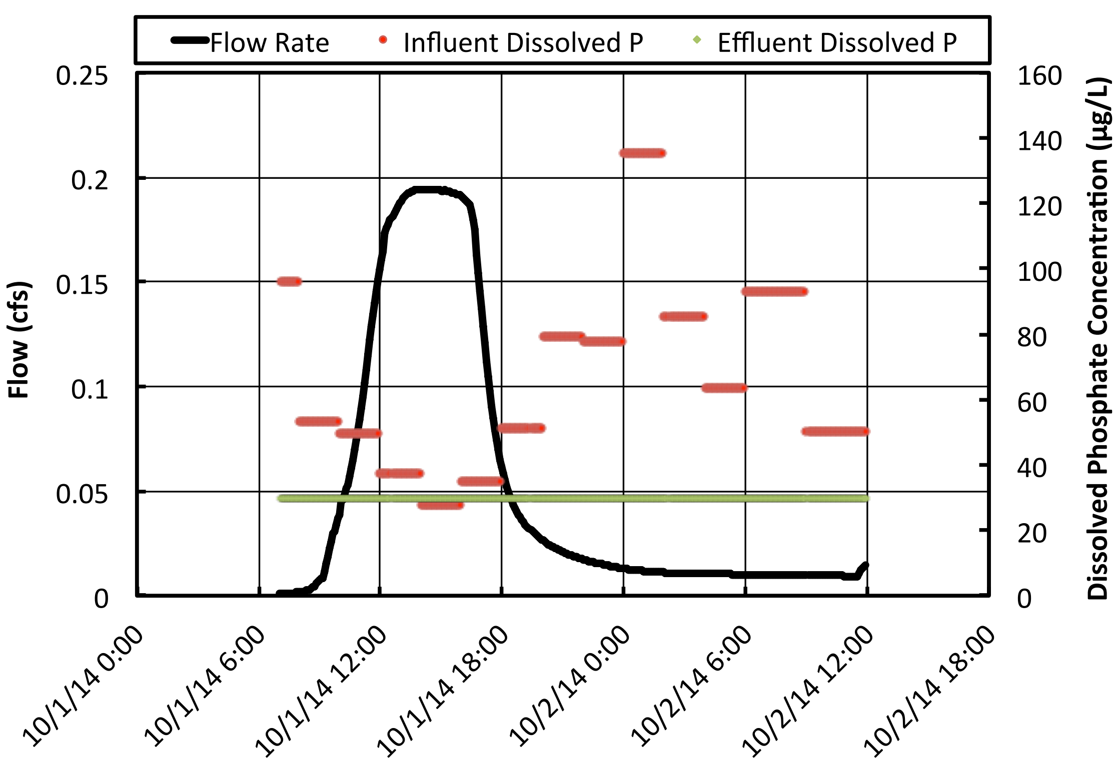

Figure B46. Flow and Pollutograph for event 23.

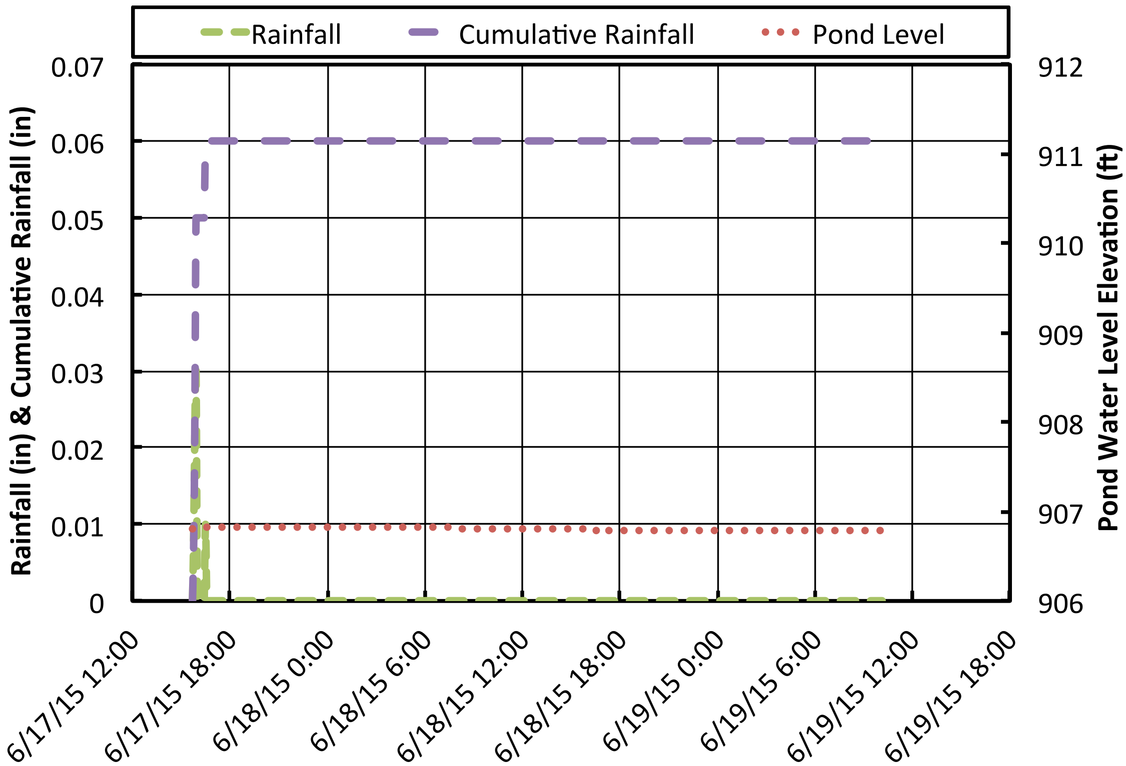

Figure B47. Rain and pond level for event 24.

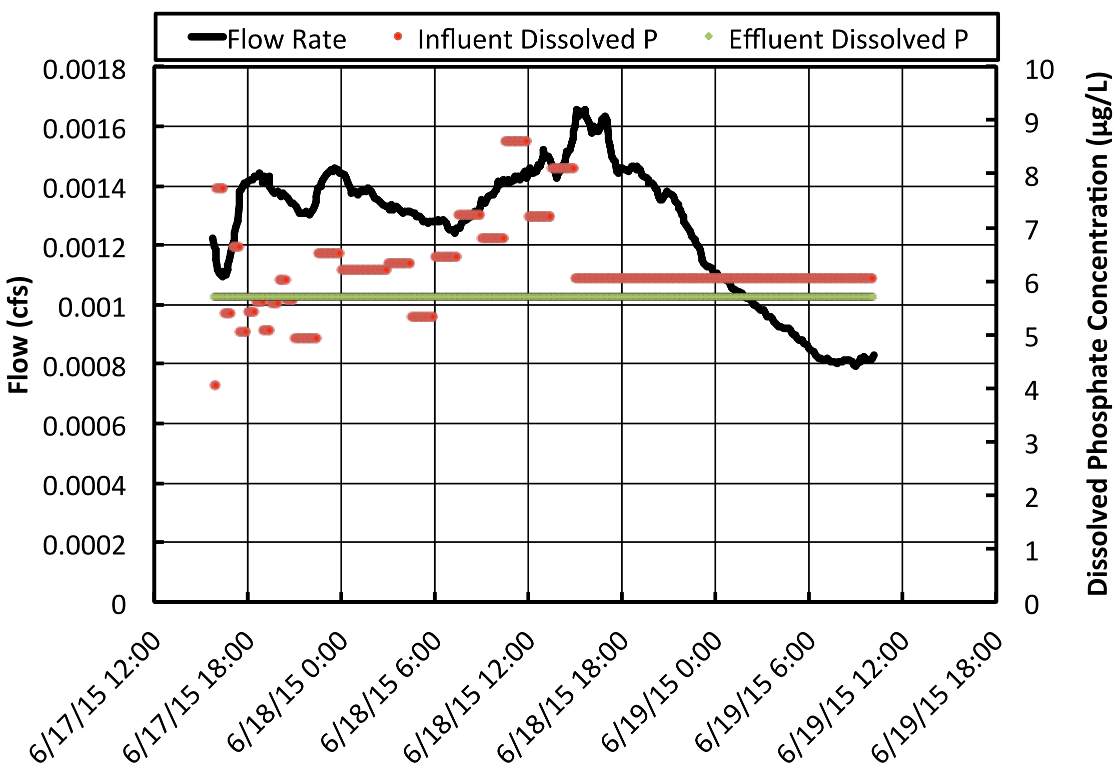

Figure B48. Flow and Pollutograph for event 24.

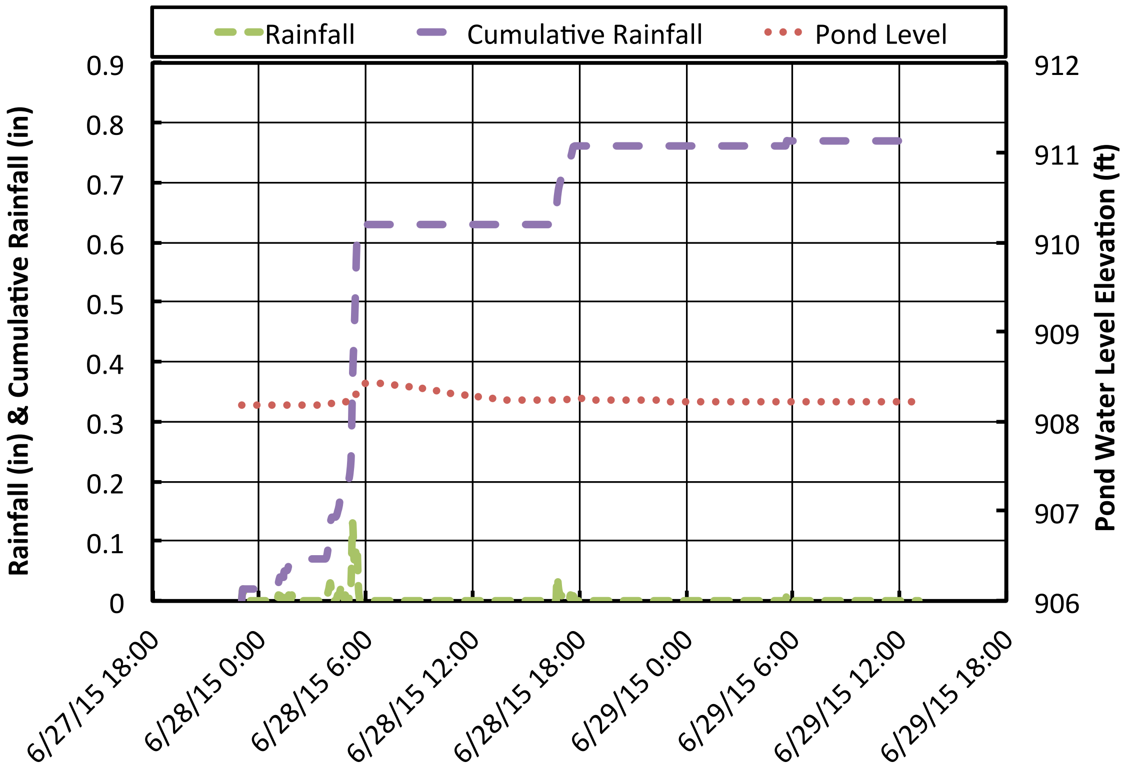

Figure B49. Rain and pond level for event 25.

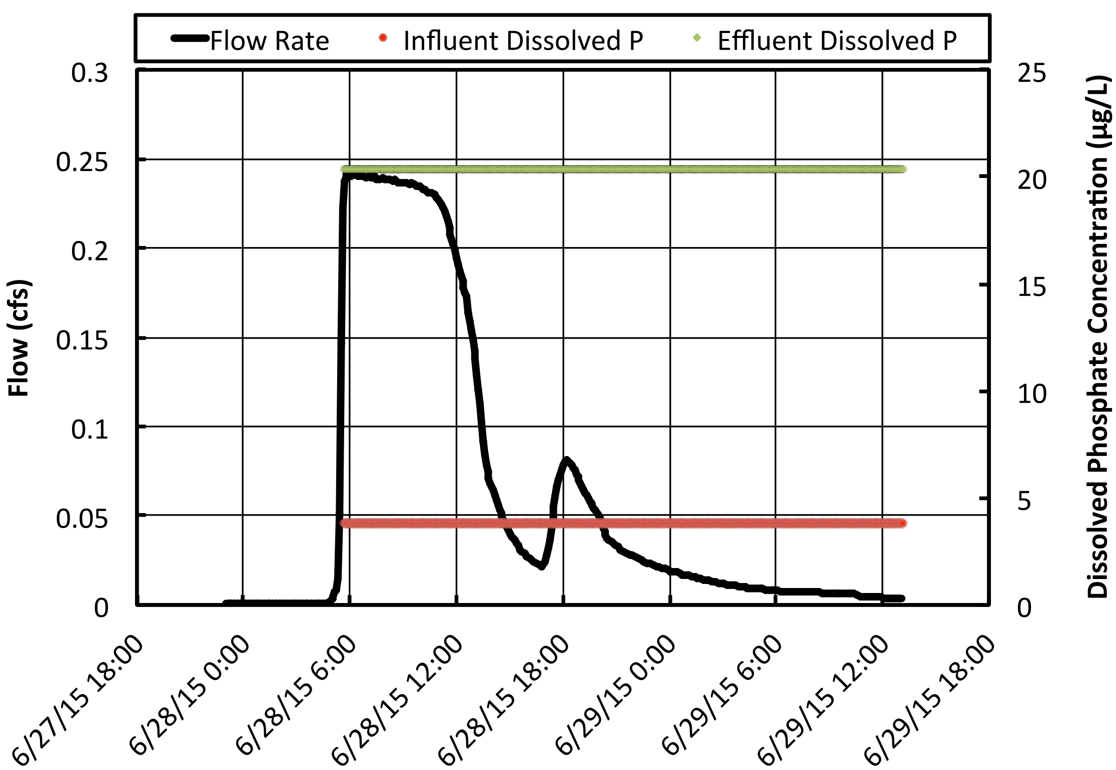

Figure B50. Flow and Pollutograph for event 25.

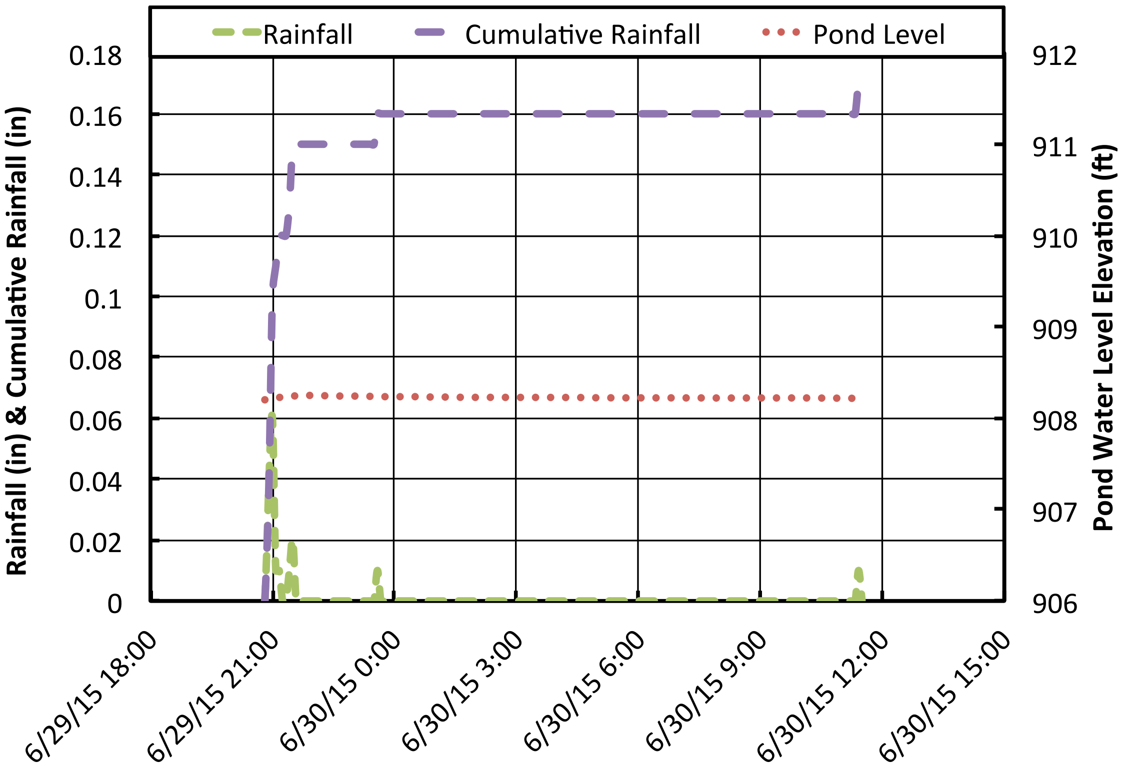

Figure B51. Rain and pond level for event 26.

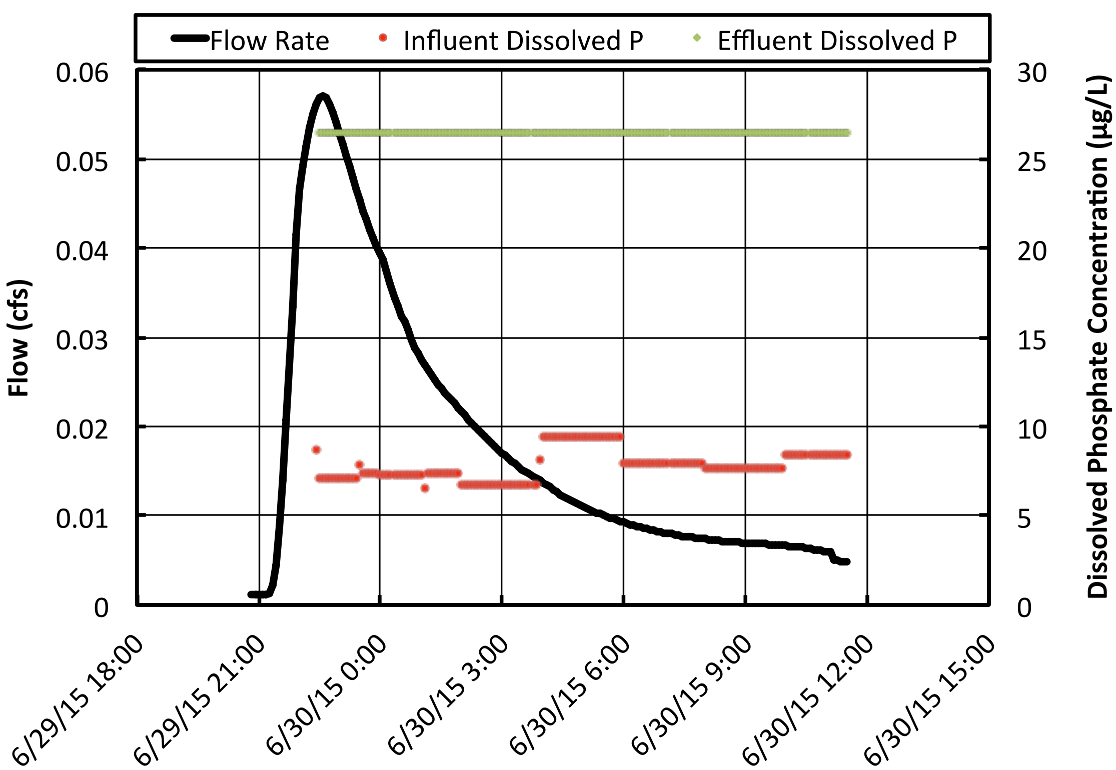

Figure B52. Flow and Pollutograph for event 26.

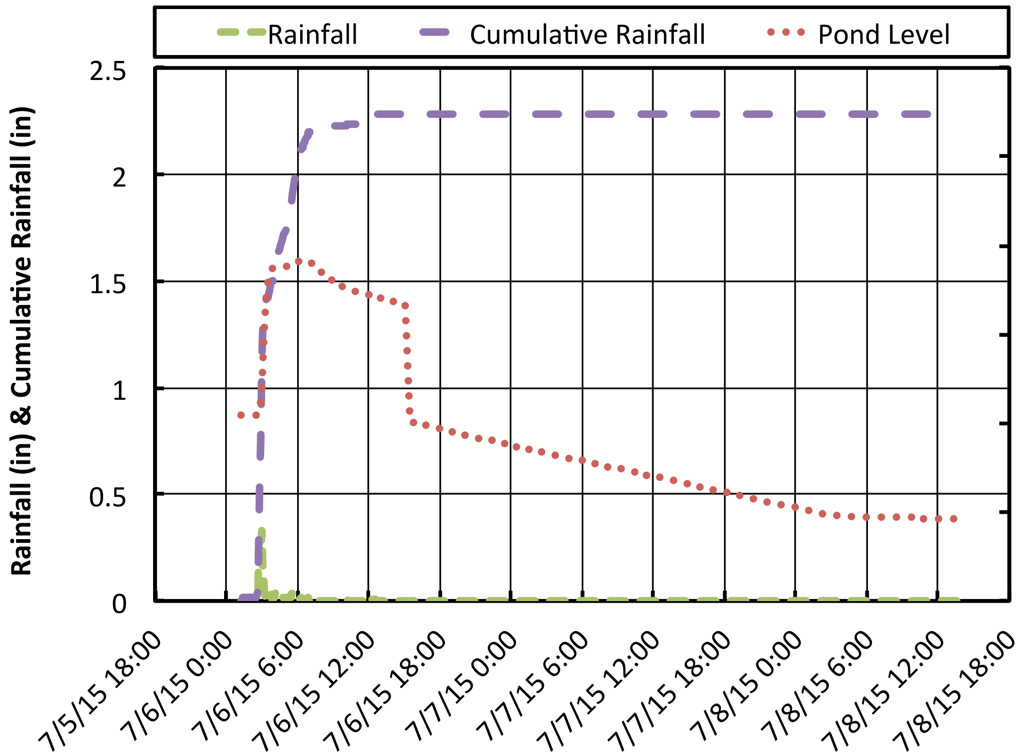

Figure B53. Rain and pond level for event 27.

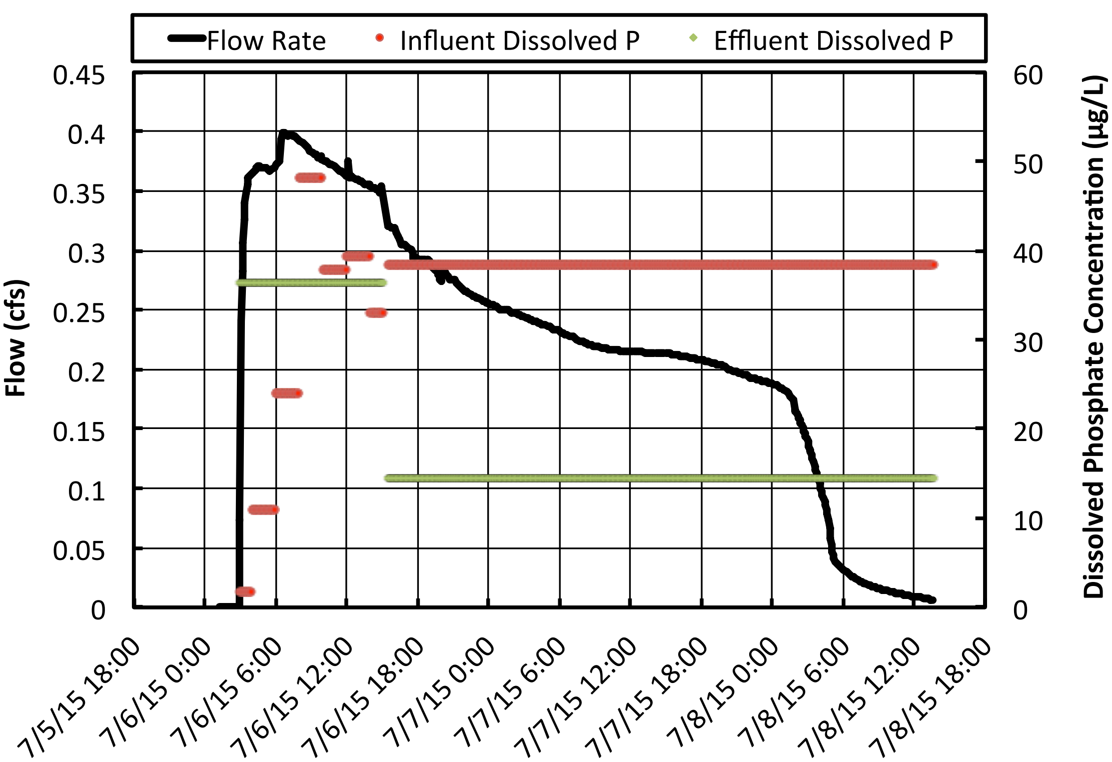

Figure B54. Flow and Pollutograph for event 27.

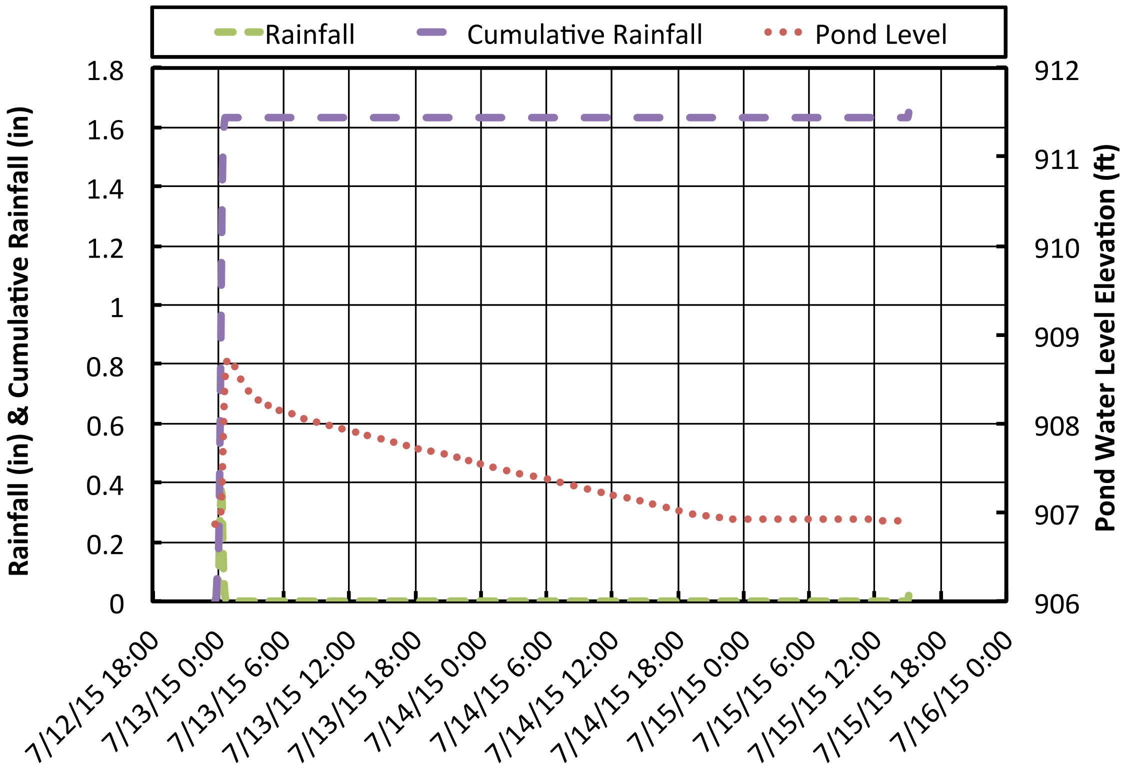

Figure B55. Rain and pond level for event 28.

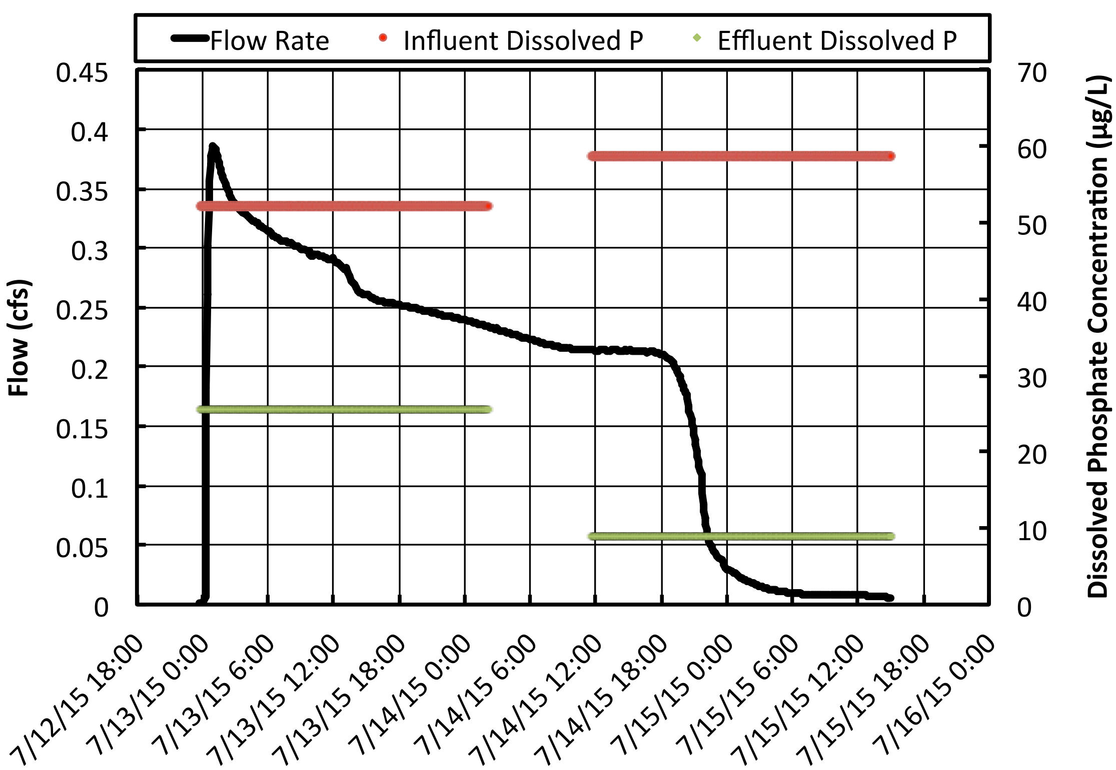

Figure B56. Flow and Pollutograph for event 28.